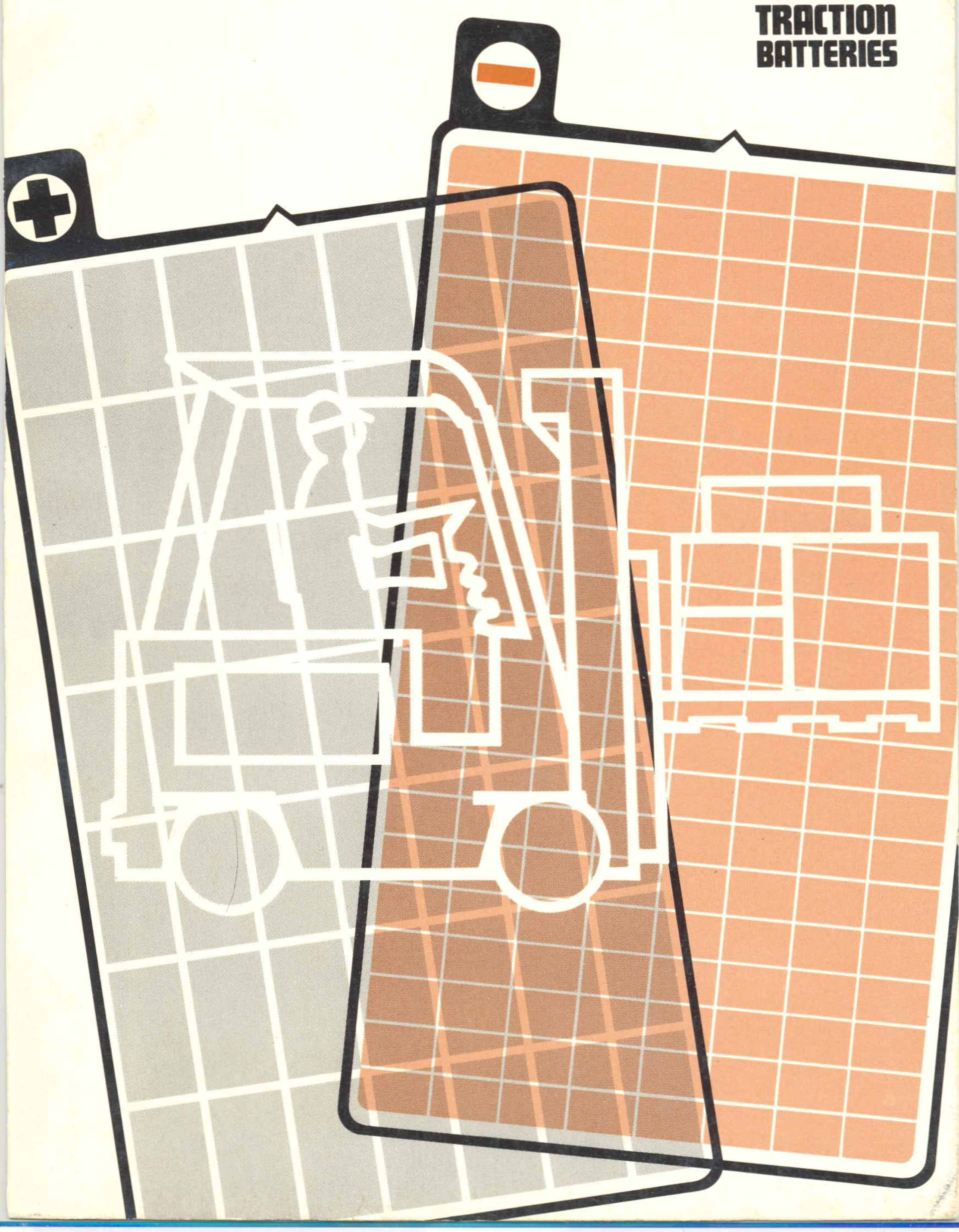
CURTIS

BATTERY BOOK ONE

LEAD ACID TRACTION BATTERIES



CURTIS

BATTERY BOOK ONE

LEAD ACID
TRACTION
BATTERIES

Written by the staff of Curtis Instruments, Inc.

Edward M. Marwell, President
Eugene P. Finger, Vice-President/Engineering
Eugene A. Sands, Vice-President/Marketing

•

Henry M. Levine, Writing Consultant

•

Ken Marsh, Editor

•

H. Shaw Borst, Inc., Design

•

CURTIS INSTRUMENTS, INC.
200 Kisco Avenue, Mt. Kisco, N.Y. 10549

Library of Congress Catalog Card Number: 81-65733
ISBN: 0-939488-00-0
First printing

Introduction

An Introductory Word

Battery Book One: Lead Acid Traction Batteries is the first of what certainly could become a series of volumes on "chemical systems capable of storing and supplying electrical energy" — batteries.

The energy crisis has focused attention on the need for alternative energy resources. Thus, where storage of electrical energy and its supply to machines, such as fork lift trucks, are required, the role of batteries is rapidly growing. Industry and government are substantially investing in the research and development of new and improved batteries for use with a wide range of electric vehicles, solar and wind power systems and as storage systems at electric generating plants. The futures of energy and batteries are undeniably intertwined.

Of the many battery types used in a variety of applications, from standby-power-supply systems to household flashlights, lead acid is one of the more important battery chemistries. These so-called "wet cells" are the principal batteries used on electric vehicles.

This book focuses on the lead acid traction battery which is the prevailing power source used for electric fork lift trucks widely employed in warehouses and factories for material handling. Though the book has been designed with the electric fork lift truck user in mind, much of the information applies to batteries in general and will be helpful to anyone interested in learning about them.

Preface

ENERGY AND FORK LIFT TRUCK BATTERIES

"Energy" is much in the news today, with good reason. Until the early 70s, the cost of electrical energy was not considered to be very important, and sometimes even went unstated in evaluating the cost of material handling operations. The "payback" of capital outlay and labor costs were the major considerations completely overshadowing the relatively miniscule costs of energy.

No longer, however, does capital outlay, or the cost of borrowed money, or of labor, etc., overshadow the cost of energy. Indeed, now, many engineering and purchasing decisions begin with an analysis of energy costs.

The reasons are obvious. Just as the shortages of gasoline and diesel fuel to operate combustion-engine vehicles have drastically increased their per-mile operating costs, so have the increased cost of generating and delivering electrical energy raised the cost of operating battery-powered fork lift trucks. Every fork lift truck is a user of energy, whether that energy is derived from gasoline or from an electric grid fed by hydro-power, nuclear power, or fossil fuels. With all three categories of energy displaying strong tendencies to increasing costs in the foreseeable future, it is entirely reasonable to expect increasing concern for improving the overall efficiency with which battery-powered fork lift trucks are operated.

As developers and manufacturers of several proprietary instruments for monitoring the performance of batteries, we at Curtis have actively pursued the subject of efficiency in battery-powered vehicles.

An early example was our design of the battery state-of-charge indicator for NASA's Lunar Rover vehicle. The object in that case was to warn the astronauts so that they would not drive too far from their base station . . . there being no means available for recharging the Rover's batteries.

A parallel program is our 933 Fuel Gage for battery-powered fork lift trucks. Here, the instrument is used to warn the driver when the truck's battery has reached the safe limit of discharge. Tens of thousands of these units are now in use on fork lift trucks throughout the world.

As we work with and listen to industry people using electric fork lift trucks, one theme emerges over and over again. "How can we minimize our energy costs?"

The purpose of this book is to assist those people in minimizing their energy costs:

- By helping them to correctly select batteries for their trucks .
- By showing them how to control the use of electrical energy in recharging their batteries.
- By helping them to avoid damaging batteries and trucks by over-discharging batteries.

The material in this book was compiled from numerous standard reference sources, from data published by manufacturers of lead acid traction batteries, from published technical papers, and from various engineering investigations carried on by Curtis as part of our ongoing study of batteries and their applications. There are, of course, no direct references to particular makes or models of truck, battery or charger. Of necessity we have generalized our examples to give them the widest possible application. Thus, where estimates of energy use, etc., are given, they are approximations based on our experience in the field and confirmed by reference to published product data. Note also that we have avoided placing specific values on capital equipment, labor, and energy.

Whenever feasible we have used nomenclature and abbreviations that conform to industry standards. In case of doubt we have relied on the standards promulgated by the IEEE/ANSI.

The text of this book has been reviewed for us by several well-known specialists in the field, and we would like to thank them individually:

Dr. David P. Boden, Senior Vice-President Technology,
C & D Batteries, Plymouth Meeting, PA.
Larry E. Heisey, Battery Charging Engineer,
Hobart Brothers Co., Troy, OH.
R. T. Josey, Mark C. Pope Associates, Inc., Smyrna, GA.
Service Engineering Department, Caterpillar Tractor Co.
(Tow Motor), Mentor, OH.
Dr. William Reinmuth, Professor of Chemistry,
Columbia University, NYC.

Curtis Instruments, Inc. • Mount Kisco, N.Y.
December 1980

Contents

Section 1.

Section 2.

Section 3.

Section 4.

OPTIMIZING ENERGY USAGE

Section 5.

WEAR AND TEAR

Illustrations

Tables

Section 1.

ENERGY, WORK AND THE STORAGE BATTERY

Energy and Work

"Energy" is the ability to do "work," a definition that relates pretty well to the world of practical experience. Everyone knows that "it takes energy to get the work done." Energy can take many forms. In addition to human "energy," there are mechanical energy, heat energy, chemical energy, electrical energy, nuclear energy, etc.

Although each of these forms of energy is in a form slightly different from the others, all share the basic feature: each provides the ability to do work.

To turn the idea around, work is the process of "spending" energy, usually in a way that we humans call "useful," although it isn't strictly necessary that the work be useful in our sense of the word. Since nature doesn't care about usefulness, expending energy in any form at all is properly called work.

Potential energy is energy accumulated in a useful form but not yet used. A relevant example is the chemical energy accumulated in a charged storage battery. Connecting the battery to a charger — which, in turn, is connected via the power lines to a distant generating plant — stores, in chemical form, a small part of the energy output of the generating plant. It makes no difference whether the energy is generated in a hydro-electric or a steam-electric plant: the same small part of the energy output of the plant is stored, as potential energy in chemical form in the battery.

When the battery is connected to the circuits of an electric fork lift truck, its chemical energy is converted into electrical energy and released, a little at a time, to the truck, which converts it into mechanical energy in the form of useful, measurable work: moving heavy coils of wire from one end of the plant to another, stacking loaded pallets, and so on. Each expenditure of energy reduces the potential stored in the battery, and so less is then available. When all of the usable energy stored in the battery has been "used up" the battery is discharged. To get more work out of it we must recharge it by restoring its supply of energy.

Whatever the source of the energy at the power lines, it takes work to generate it, accumulate it, and transmit it, and more work to convert it into chemical form in the recharged battery. For practical purposes, all of these processes — from generating to charging — are part of the energy cost and are basic components of every electric truck operator's utility bill.

Energy and Power

Energy is the ability to do work and power is the rate at which the work is done. Lifting 55 pounds 10 feet in the air takes 550 foot-pounds of energy, and doing that much work in 1 second is 550 foot-pounds per second or 1 horsepower.

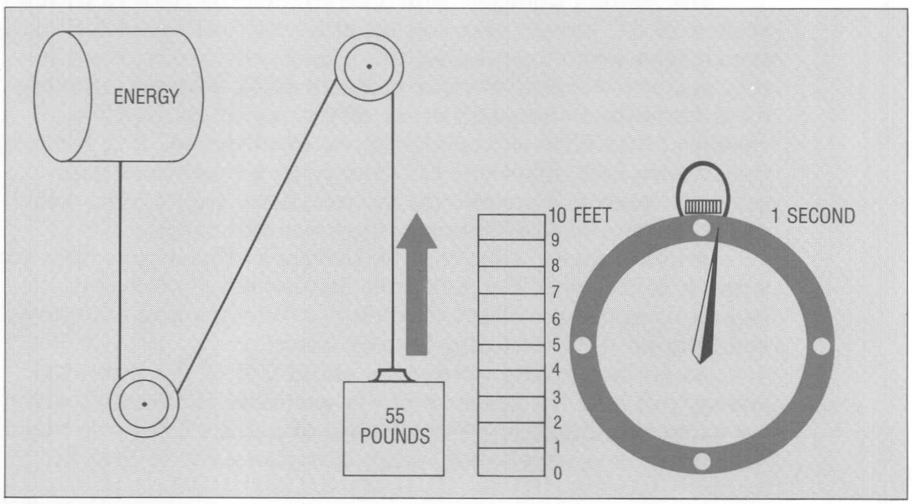
The term horsepower was invented in the 18th Century to create a practical unit for the rate of doing work. Presumably, it represents working "as fast as a horse," a rate we define as 550 foot-pounds per second. (Figure 1.)

Another unit used to represent the rate of doing work is the "watt." Because both the horsepower and the watt represent rates of doing work, they can be equated to one another, and it turns out that 1 horsepower is the same rate of work as approximately 750 watts*.

Where work and energy are concerned, only the total amount accumulated or spent matters . . . not how quickly or slowly. Where power is concerned, however, the time factor enters. The faster a given amount of energy is spent, the higher the power rating; the slower the same amount of energy is spent, the lower the power rating.

**Here and elsewhere, we have deliberately rounded values to simplify arithmetic.*

Figure 1: Horsepower



Accumulating Energy

There are many ways to accumulate energy. For example, feeding our horse so that he can work — that is, deliver horsepower — is one way of accumulating energy, and so is charging a storage battery, which is actually called an accumulator in some other countries.

In accumulating energy, the important considerations are: the quantity of energy to be stored in the accumulator; the form in which the energy is accumulated, stored, and released for use; and the overall efficiency of the process of accumulating, storing, and releasing the energy.

In the lead acid storage battery, large quantities of energy are accumulated by chemical activity that is produced by the charging process.The energy is then released on demand in the convenient form of electric current.

Energy Efficiency

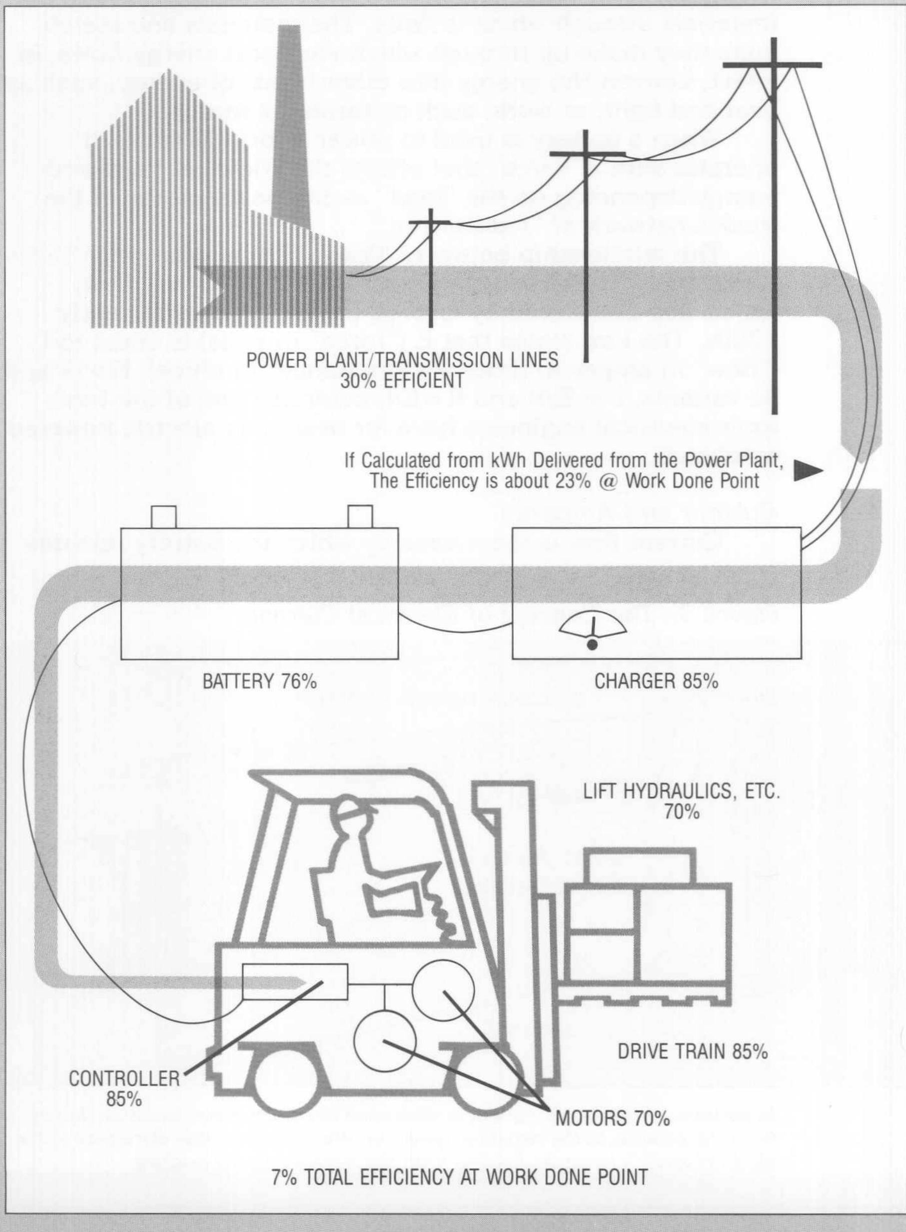
With charging and discharging batteries, as with all energy transfer processes, energy losses occur. The inequality between what is put into a system and what is drained from it is the system's energy efficiency. Generally, the energy efficiency of lead acid batteries is about 76%, meaning that 76% of the energy that was put into the battery during charging is all that is available for release during discharge. The energy efficiency is given as an approximate number since discharge rates and temperature can affect it.

The battery charger, which interfaces the battery with a source of AC power, also has an efficiency rating and, thus, is considered when calculating the overall efficiency of a battery system. A good charger is about 85% efficient, making for a combined charger/battery efficiency of about 65%, meaning that 65% of the electricity from the AC line fed into the battery is available as DC energy to a machine's components, such as controllers, motors, drive trains, etc., which are also not 100% efficient in their use of energy.

Another factor affecting the battery's efficiency is how and when it is charged. For a further discussion of charging regimens and their effect on energy efficiency and economy, see Section 4, Optimizing Energy Usage.

As an interesting note: only about 7% of the potential energy put into the power plant is available for actual work; for example, the lifting and moving of pallets from one place to another in a warehouse, when using an electric fork lift truck.

Figure 2: Energy Efficiency from Electric Generation Plant to Work Done by Electric Fork Lift Truck



Ohm's Law

Our use of electrical energy is dependent on the "flow" of electrical energy, the magnitude of the "force" propelling it and the "resistance" to its flow that naturally occurs in all materials through which it flows. The materials and the circuits they make up through which electrical energy flows, in effect, convert the energy into other forms of energy, such as heat and light, or work, such as turning a motor.

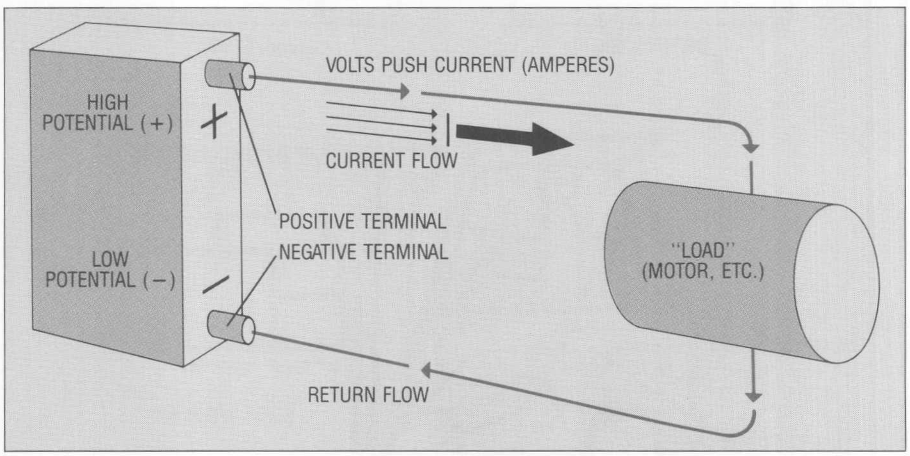
When a battery is used to power a fork lift truck, it operates with a "force" that affects the "flow" of its stored energy depending on the "load" — the power needs of the truck's network of "resistances."

The relationship between "flow", "force" and "resistance" is expressed mathematically in Ohm's Law, which was discovered by George Simon Ohm in the early 1800s. The Law states that E ("force" in volts) is equal to I ("flow" in amperes) times R ("resistance" in ohms). $E=IR$ and its variants, $I = E/R$ and $R=E/I$, comprise one of the basic tools electrical engineers have for designing electric powered machines.

Current and Amperes

Current flow is the means by which the battery releases

Figure 3: The Concept of Electrical Current



In sections of this book, current is discussed in conventional terms as flowing from the positive to the negative; while, in other sections, it is discussed in the electrochemist's terms as flowing from the negative to the positive.

its energy in electrical form. Current is the flow of electric charge from the positive terminal of the battery through the "load" (motors, pumps, controllers, etc.) of the truck, and back to the negative terminal of the battery. (Figure 3.)

The flow of current from the battery depletes the battery's stored charge. The rate of that depletion or current drain is measured in amperes. An ampere is the flow of 1 coulomb* per second. It is also defined as the amount of current that can be forced through a resistance of 1 ohm by an electrical potential of 1 volt.

The Volt

The volt is the unit of electrical potential, or pressure, that "forces" the current from the battery through the load and back to the battery. Since batteries are made up of many cells connected in series the total voltage of a battery, naturally, is the sum of the voltages of all its cells. A typical lead acid battery used in a fork lift truck may have 18 cells, nominally 2 volts each; the nominal battery voltage is therefore 36 volts.

The Watt

The watt is the electrical unit that defines the rate at which work is done, or energy is spent. Mathematically, we can say that Watts = Volts × Amperes.

The bigger the current (amperes) and/or the voltage (volts), the faster the stored energy can be converted into work.

The Kilowatt-Hour

If the watt is the rate of doing work, then the total amount of work actually done is the product of watts and hours: watt-hours. If a battery delivers 1000 amperes at 24 volts for 2 hours, the total amount of energy delivered is

1000 × 24 = 24,000 watts × 2 hours = 48,000 watt-hours.

To keep the significant digits from attracting too many zeros, we use the prefix "kilo" (k), which means 1000, and, sometimes, "mega" (M) for millions. The energy delivered in this example is therefore 48 kilowatt-hours.

**The coulomb is a unit of electrical energy that has been in use since before the discovery of the electron.*
It is actually made up of 6,000,000,000,000,000,000 electrons.

A rating of 1000 watt-hours (1 kWh) is equivalent to 1 horse working 1⅓ hours.

Where batteries are concerned, the kilowatt-hour rating at a stated discharge current is an accurate description of exactly how much energy the battery can deliver before it is discharged. Since electric bills are rendered on the basis of the number of kilowatt-hours of usage, it is often useful to make calculations about energy usage and efficiency directly in kilowatt-hours.

The Ampere-Hour

An ampere-hour is the total amount of electrical charge transferred when a current of 1 ampere flows for 1 hour. Therefore, the total usable charge stored in a battery can be stated in terms of ampere-hours — how long a current of a particular amperage can be drawn from the battery.

The ampere-hour rating accurately predicts the battery's capacity at a specified load current; batteries are therefore rated in ampere-hours at specified currents. A battery that can be discharged at 125 amperes for 6 hours before reaching its end-point voltage is rated at 125 amperes × 6 hours = 750 ampere-hours. Its "capacity" is therefore stated as "750 ampere-hours at the 6-hour discharge rate (at +25 °C)."

Battery Capacity

The term battery capacity relates to the amount of usable electrical energy stored in the battery. It is important to keep in mind that a manufacturer's rated capacity is given for 100% discharge of the battery. The recommended usable capacity, however, is generally 80% of the rated capacity to insure maximum battery life. For practical purposes, battery capacity is usually stated in ampere-hours because a particular number of ampere-hours of capacity is equatable to operating a given vehicle for a given length of time before its output voltage reaches the end point. A battery rated at 1200 ampere-hours is, therefore, thought of as maximally having 960 ampere-hours of usable capacity. Capacity is also affected by discharge rate and other variables that are discussed more thoroughly in the following pages.

Most manufacturers also provide capacity ratings in terms of kilowatt-hour specification when describing their batteries. As with ampere-hour ratings, the conditions under which kilowatt-hour specifications are determined must be specifically stated to be meaningful.

End Point Voltage (Final Voltage)

Today's lead acid traction battery has a downward-curving discharge characteristic, meaning that the voltage of the battery decreases gradually as it is discharged. The end point voltage is that which determines that the battery is discharged. Defining an end point voltage is an attempt to provide users with a cut-off beyond which the battery should not be used or damage to it and the equipment it is powering may occur.

Depending on the rate of current drain and the equipment, end point voltage can vary. However, when a usage pattern of the battery and equipment are predictable, as is pretty much the case with fork lift trucks, an end point voltage is quite meaningful.

The end point voltage for electric fork lift truck applications is selected by general agreement among battery and truck manufacturers. Still, for a 2 volt cell, there are differing opinions on just where the end point should be set with a normal range lying between 1.65 and 1.75 volts per cell (with the battery "loaded"). In some cases, especially at high discharge rates, this range is extended as low as 1.2 volts per cell by some manufacturers.

Battery manufacturers may suggest that their batteries can safely be discharged beyond the accepted range of end point voltages. No significant loss of battery life will be caused by such operation, they say. Further, they may even maintain that such operation is cost-effective as far as battery life is concerned.

Truck manufacturers, however, may take a different position. They say that allowing the battery voltage to fall appreciably below the specified end point may do irreparable damage to electrical equipment installed on the truck. They point out that operating at undervoltage can, for example, overheat motors causing ultimate failure and/or burn relay contacts.

From the users' point of view, though, one kind of damage may be as bad as another. A damaged battery must be replaced; a damaged pump motor or other component must be repaired or replaced. In either case, loss of the use of the truck — down time — is a problem that may be more severe than the physical damage. Users, therefore, may have more of an interest in establishing — and accurately detecting — the end point voltage than either of the two suppliers.

Section 2.

ABOUT LEAD ACID BATTERIES

Introduction

There are two types of lead acid batteries generally used for vehicle applications — the ordinary automotive battery (used for starting, lighting, and ignition) and the traction battery used to supply motive power for electric vehicles. Automotive batteries are designed for infrequent, very high current drains of short duration, and recharging begins as soon as the engine reaches operating speed. Traction batteries, on the other hand, are designed to be discharged continuously at relatively moderate current drains because there is no practical way to recharge the battery during operation. The stored charge of a traction battery, therefore, runs steadily down from its starting condition until the battery is recharged. A reasonable service life from such a battery might be considered as 1000 to 2000 cycles of discharge and charge; and typical life spans for industrial batteries, properly used and cared for in fork lift trucks, are about 5 years, sometimes even longer.

Figure 4 shows typical charge/discharge characteristics for batteries used in two common commercial applications —a taxi and a fork lift truck, both used in 2-shift operations.

How a Lead Acid Battery Is Made

The lead acid battery is made up of several identical cells, each of which contains two plates, one positive, the other negative. Both plates are immersed in an electrolyte that is a mixture of sulfuric acid and water.

Two types of cell construction are common: flat plate and tubular plate. The overall functions of the two types are identical, but their mechanical construction and performance differ slightly.

In a flat plate cell (Figure 5), each positive plate is a cast metallic lead frame which contains the lead dioxide active material. The negative plates contain spongy metallic lead active material within a similiar grid structure. Positive and negative plate areas are usually identical.

In a tubular plate cell (Figure 5), the positive plates surround lead alloy spines. The lead dioxide is in close contact with the spine over its entire length, and is retained by a special sleeve. Negative plates are of spongy metallic lead in a grid form identical to those in flat plate cells.

Figure 4: Battery Charge/Discharge Cycles in Two Commercial Applications

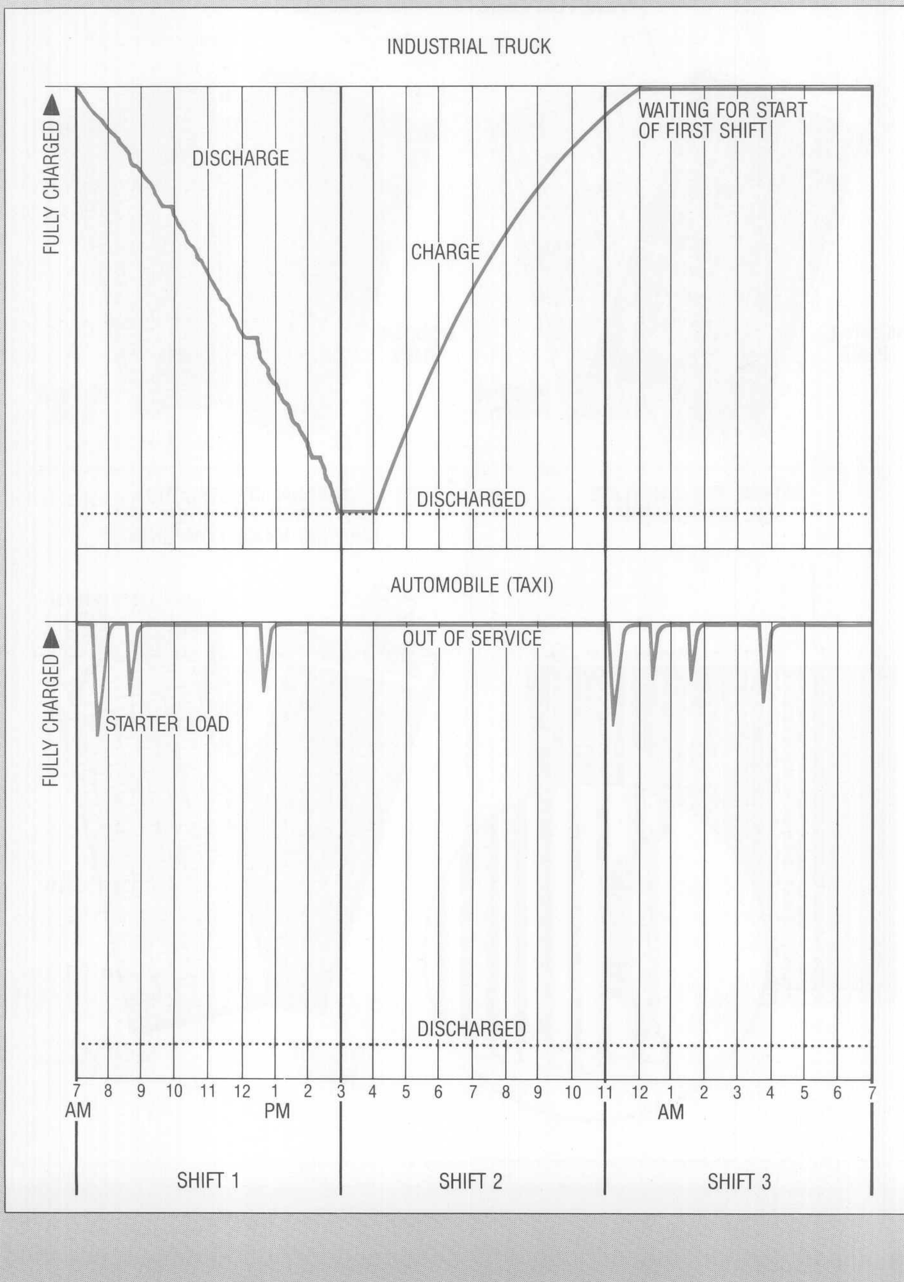
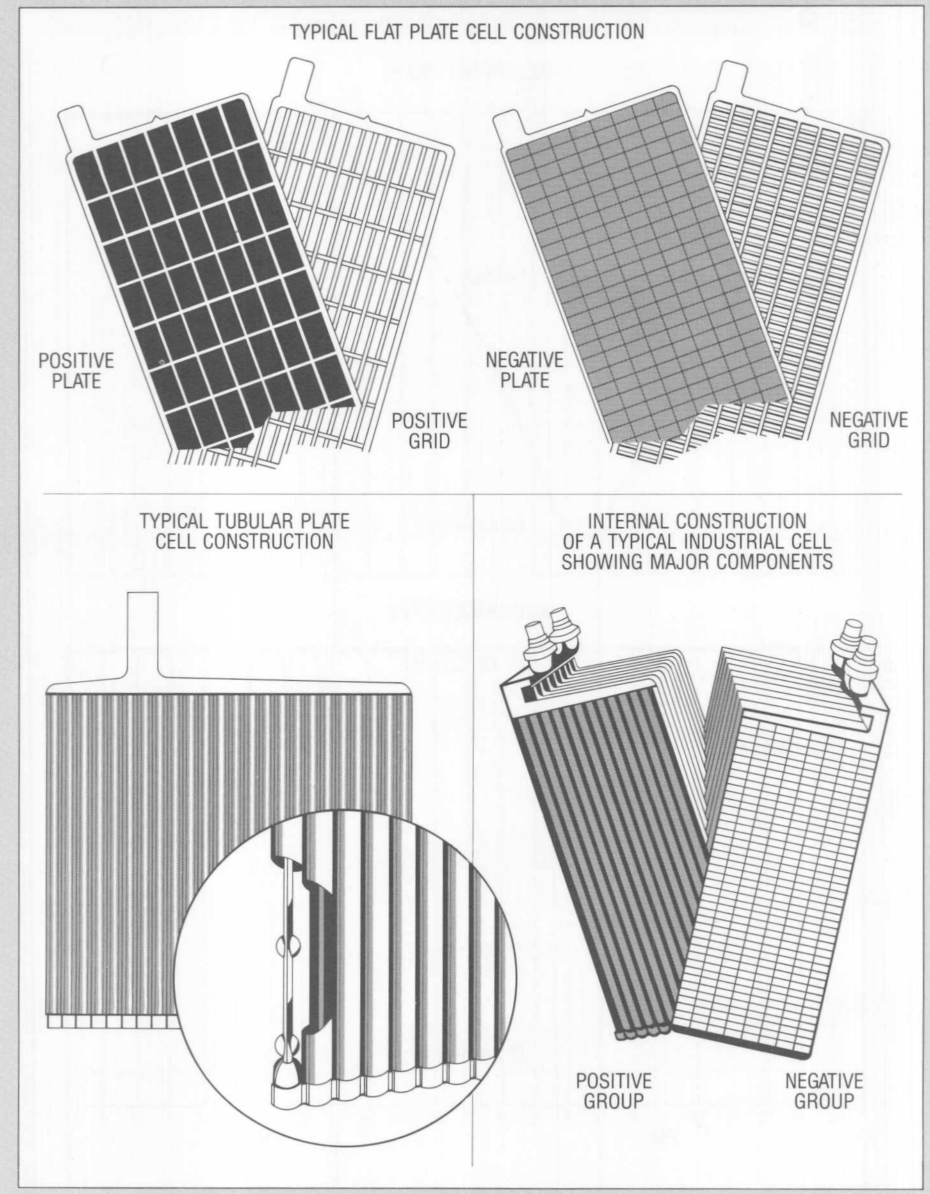


Figure 5: Typical Flat Plate and Tubular Plate Cell Construction

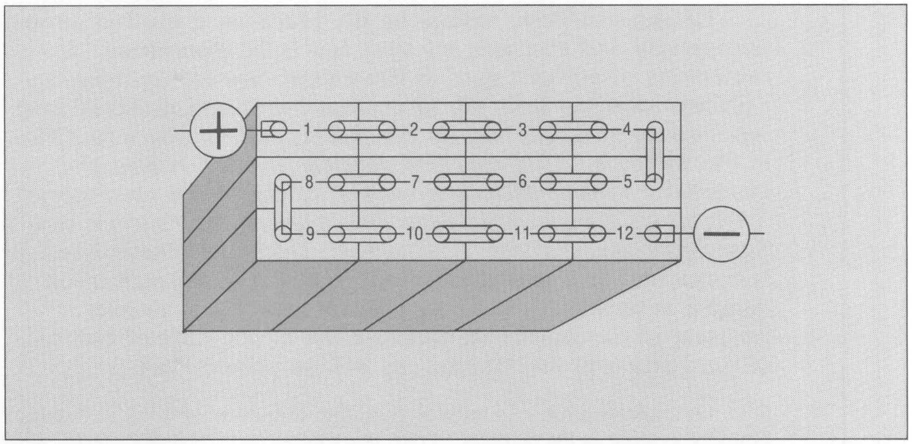


In either case, the cell is filled with electrolyte, which is slightly heavier than water. The ratio between the weight of a given volume of electrolyte and the same volume of water is the specific gravity of the electrolyte.

Figure 5 shows how a typical industrial cell is assembled. In order to provide sufficient current output (amperes) each cell consists of many plates (for example, 11 positive and 12 negative). Because each positive plate is positioned between two negative plates, there is always one fewer positive than negative. The positive plates in each cell are connected in parallel to provide a positive bus of the required current output, which is connected to the positive terminal of the cell. Similarly, the negative plates are bussed and connected to the negative terminal.

The cells are connected by external metal straps that hook them into a series circuit . . . a circuit in which the negative plates of one cell are connected to the positive plates of the next, so that the voltages of all cells are added to provide the total voltage of the battery. Typically the cells are numbered in sequence beginning with the cell containing the positive terminal of the battery (number 1) and ending with the cell containing the negative terminal. (Figure 6.) There can be any number of cells in a battery, but the numbers most commonly used are: 3, 6, 9, 12, 15, 16, 18, 20, 24, 30, 36, and 40.

Figure 6: Battery Cell Strapping and Numbering



Battery rating information is generally displayed in coded form, stamped into the lead of the first negative terminal or on a nameplate on the side of the battery. As an example, the code for a particular battery might read as follows:

12	C	85	11
Number of cells	Manufacturer's Cell Type	Ampere-hour Capacity per Positive Plate	Total Number of Plates Per Cell (5 Positive, 6 Negative)

The ratings for this battery are:

Voltage: 12 cells × 2 volts each = 24 volts

Capacity: $\frac{11 - 1}{2}$ positive plates × 85 Ah each = 425

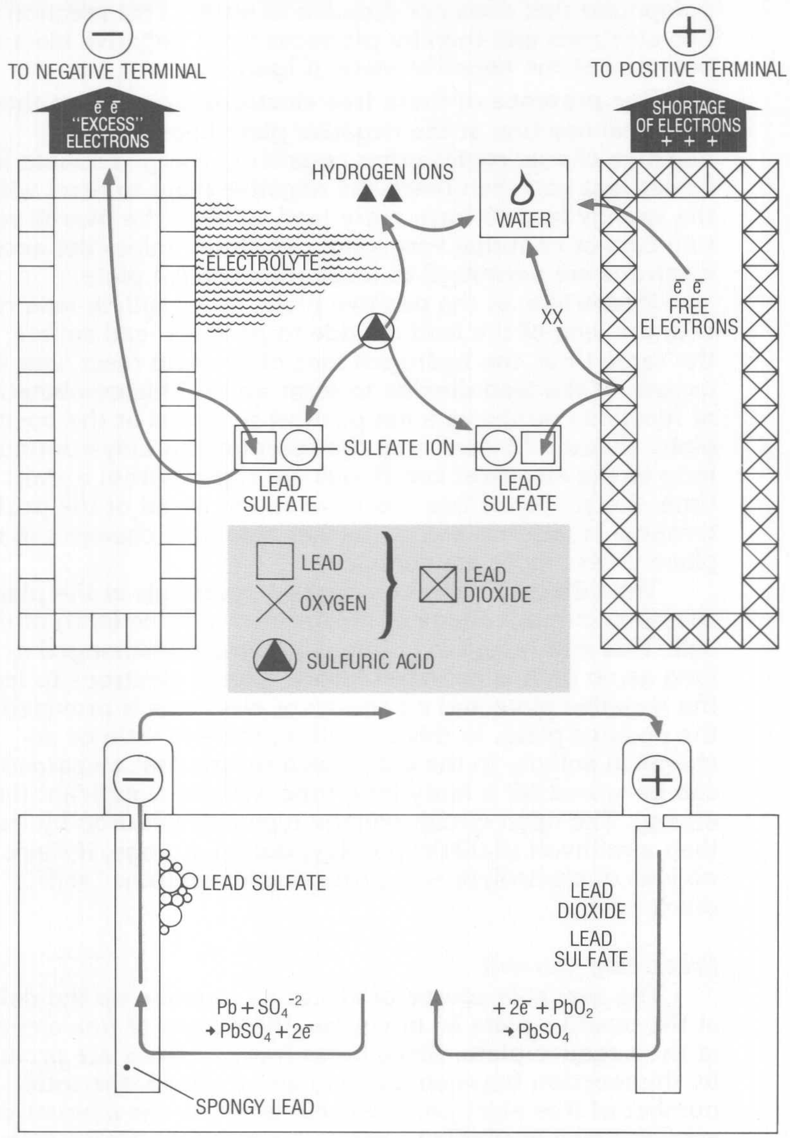
Electrolyte

The electrolyte in a lead acid battery is a mixture of sulfuric acid and water. Sulfuric acid is a very active compound of hydrogen, sulfur, and oxygen. Its chemical formula is H_2SO_4. In water, the sulfuric acid molecules separate into two ions, hydrogen and "sulfate," the latter of which is made up of sulfur and oxygen atoms. Each sulfate ion contains two "excess" electrons and each therefore carries two negative electrical charges. Each hydrogen ion, having been stripped of one electron, carries one positive electrical charge.

Because sulfuric acid is highly reactive, it ionizes almost completely and so there are very few fully assembled molecules of sulfuric acid in the electrolyte at any instant. Furthermore, the ions are in constant motion, attracted and repelled by one another, by the water, and by any impurities in the mixture. This constant random motion eventually causes the ions to diffuse evenly throughout the electrolyte. If any force disturbs this even distribution, the random motion eventually restores it. However, since the electrolyte is contained in a complex structure of cells, redistribution takes a relatively long time. This fact turns out to play a key role in our ability to measure the exact state-of-charge of the battery at any instant, as will be shown later.

In sections of this book, current is discussed in conventional terms as flowing from the positive to the negative; while, in other sections, it is discussed in the electrochemist's terms as flowing from the negative to the positive. ▶

Figure 7: Schematic Representation of Reactions at Negative and Positive Plates



NET REACTION: $Pb + PbO_2 + 2H_2SO_4 \rightarrow 2PbSO_4 + 2H_2O$

Producing an Open Circuit Voltage

The chemical reaction between the sulfate ions and the spongy lead of the negative plate produces lead sulfate, a compound that does not dissolve in water. This reaction frees two electrons and thereby produces a net negative electrical potential at the negative plate. (Figure 7.)

The presence of these free electrons slows down the chemical reaction at the negative plate because their negative charge repels other negatively charged sulfate ions. Fewer ions can then reach the negative plate to react with the spongy lead to form more lead sulfate. The overall reaction cannot continue very long, therefore, unless the excess electrons are permitted to leave the negative plate.

Meanwhile, at the positive plate, other sulfate ions react with the lead of the lead dioxide to produce lead sulfate; at the same time, the hydrogen ions of the acid react with the oxygen of the lead dioxide to form water. This combination of reactions produces a net positive potential at the positive plate. (Figure 7.) Here, too, the reaction can only continue as long as the electrical conditions are right. Within a short time, the supply of free electrons in the metal of the positive terminal is used up and no further chemical change can take place unless more are supplied.

The difference between the two potentials at the plates is the open circuit voltage or electromotive force (emf) of the cell. This emf (about 2.1 volts) will remain unchanged as long as no path is provided for the excess electrons to leave the negative plate and no source of electrons is provided for the positive plate. In this condition, there is little or no chemical activity in the cell, which means that a charged cell can be stored for a fairly long time without significant loss of energy. The open circuit voltage typically will drop by less than a millivolt (0.001V) per day, during storage, if there is no loss of electrolyte — a process referred to as "self-discharging."

Producing Current

The available source of electrons to make up the deficit at the positive plate is, of course, the excess of free electrons at the negative plate. Since these free electrons are produced by the reaction between the acid and the lead, the total number of free electrons available is set by the amount of acid and lead available to react. A similar limitation exists for the positive plate; the total number of free electrons it

can absorb is set by the amount of acid and lead dioxide available to react.

Since any flow of electrons is a transfer of charge, the total amount of charge stored in the cell is established by the total amounts of plate material and sulfuric acid available to react. The total amount of charge stored in the cell determines the capacity of the cell.

If a wire is connected between the two plates, the excess electrons instantaneously rush from negative to positive. This electron current* is very high because the wire is a short circuit between the terminals. If the wire is very thick (has no resistance at all), the total number of electrons transferred is determined only by the amount of electrolyte that has reacted — and continues to react — with the two plates. The net charge transfer is 2 electrons per molecule of acid. Since the number of molecules of acid is inconceivably large, a gigantic current could flow between the shorted terminals, transferring nearly all of the cell's stored charge from one terminal to the other in a very short time.

If electrical resistance . . . a load . . . is connected between the terminals, then the current is limited by the resistance of the load, and the cell's charge is transferred from terminal to terminal, via the load, at a slower rate, *i.e.,* a smaller electron current. For a typical traction cell, the current can be hundreds of amperes. This current will flow as long as the load is connected and as long as there is active material left in the cell to sustain it.

Since no physical process is perfect, the electrolyte/plate reactions offer resistance to this internal current and therefore lose some of the transferred energy in the form of heat. The electrical effect of this internal resistance of the cell appears as a loss of potential (a voltage drop) at each plate. The cell's total voltage under load is therefore less than its open circuit voltage. The amount of energy lost to this internal resistance depends on the load current and on the concentration of acid in the cell . . . especially the acid concentration at the positive plate. The larger the load

**When discussing the electro chemical reactions in a battery, it is useful to refer to electron flow as current.*

current, the greater the loss of energy. Also, the lower the acid concentration at the plates, the higher the internal resistance of the cell.

When current is produced by the cell, acid, lead dioxide and lead are converted to lead sulfate and water. Each acid molecule that reacts is no longer part of the electrolyte. This process, by reducing the concentration of acid in the water, gradually reduces the ability of the cell and leaves less energy in it.

In the design of batteries, the amounts of acid and plate-active materials are balanced so that the release of energy relates to the rate at which current is likely to be drawn. Batteries designed for low-rate applications, such as for storage in solar power systems, contain a larger amount of acid in proportion to plate-active material. They are designed to be plate-limited when used beyond their rated capacity. No plate materials will be available for releasing usable energy.

Batteries designed for high-rate applications, such as automotive ignition, etc., have a smaller amount of acid in proportion to plate-active material. They are designed to be acid-limited when used beyond their rated capacity.

As acid concentration becomes too low, a cell becomes incapable of releasing usable energy at the rate for which it was designed. Additional energy can only be drawn from it if the current rate is reduced. As it is driven to excessively low acid concentrations (through deep discharging), the coatings of lead sulfate produced by the chemical reactions at the plates will not reconvert. Upon charging, acid concentration is restored and plate coatings will again reconvert.

The traction battery used with fork lift trucks falls between the automotive and storage battery in its proportion of acid and plate-active material. It is generally considered to be acid-limited for rates exceeding the 6-hour capacity.

State-of-Charge

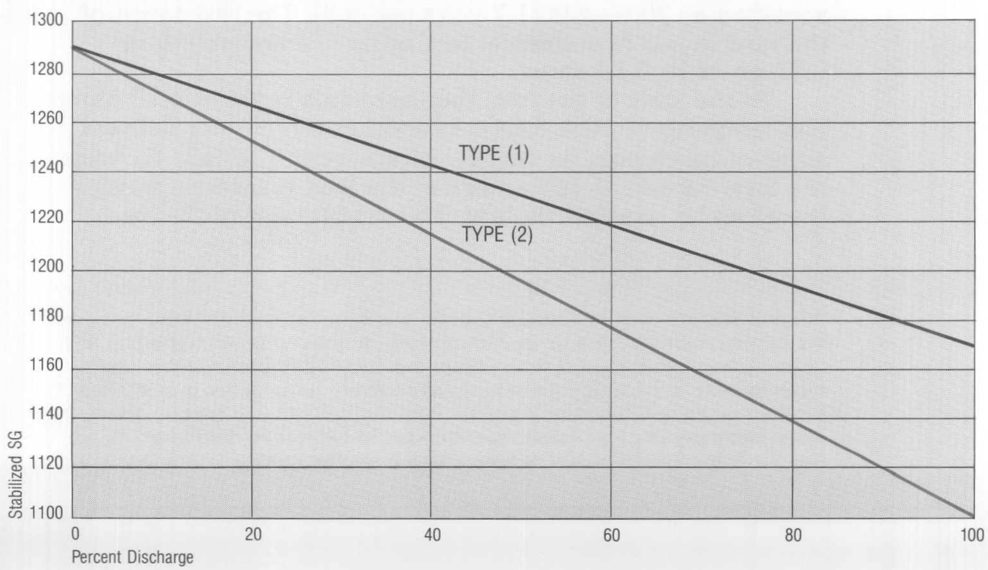
The cell's state-of-charge is determined by the amount of active material available to sustain a usable current flow through a load. At the outset, all of the active material is available and the cell is fully charged. When it can no longer produce usable current, the cell is fully discharged. At any

point between these two extremes, the state-of-charge of the cell is expressed as a percentage of the total difference in charge between the fully charged and fully discharged states.

Since the state-of-charge is set by the availability of active material in the cell, it is *conventional* (but not alone sufficient) to define the cell's state-of-charge in terms of the specific gravity of the electrolyte. As defined above, specific gravity, a measure of density, is the ratio of the mass of the mixture of sulfuric acid and water in the electrolyte to pure water at a specified temperature. It is common to speak of, for example, 1300 SG in lieu of 1.300 specific gravity: a convenience simply achieved by multiplying 1.300 by 1000. For the purposes of this book, from this point on, specific gravity measurements shall be expressed in SG form. All SG measurements are corrected to + 25°C.

The relationship between state-of-charge and specific gravity is usually shown in a form similar to Figure 8. Note, however, that this illustration does not take into account the dynamic activity inside the cell while current is flowing. It shows only the long-term average relationship when the load has been disconnected and the sulfate ions have had a chance to diffuse evenly throughout the cell.

Figure 8: Stabilized SG for 2 Cell Types Vs State-of-Charge at the 6-Hour Rate



The time required for this diffusion process to be completed varies according to the rate, depth and length of discharge and is different in cells of different design. Figure 9 shows this effect as measured on a typical cell that has been discharged at a moderate rate. In this test, it took more than 16 hours for specific gravity to fully stabilize.

Since the lead sulfate forms at the plates, the specific gravity of the electrolyte is lowest near the plates and highest farther from them. Measuring specific gravity during or shortly after discharge actually provides false information about actual average specific gravity, with an error factor that depends on the depth and duration of the cell's recent discharges.*

Determining Battery Capacity

Battery capacity is determined through manufacturer testing. Manufacturers have test procedures which are utilized to establish the hour rate and ampere-hours of their batteries. Prior to making a capacity measurement, the battery is fully charged (typically 1290-1300 SG). Then it is connected to a load that draws a desired current. The battery's output current and its voltage are monitored continuously for the specified time. A conventional test setup is shown in Figure 10. In this case, the battery capacity was intended by its manufacturer to be 960 ampere-hours at the 6-hour rate; that is, the battery is designed to be capable of delivering 160 amperes for 6 hours. The final (end point) voltage is specified as 30.6 volts (1.7 volts per cell). The resistance of the load in our hypothetical test setup is adjustable from 0.23 ohms to 0.19 ohms.

At the start of the test, the resistance is set to 0.23 ohms (160 amperes at 36.4 volts). As soon as the battery delivers some of its charge, its output voltage begins to fall. To keep the load current at 160 amperes, the load resistance must therefore be reduced slightly. This adjustment of the load

**In practice, the daily measure of specific gravity is made at the same point in the battery's operating sequence (for example, at the end of each shift). In this case, approximately the same conditions will have been reached when the measurement is made and the results will therefore be fairly consistent. Such measurements will, however, be offset from the true value of specific gravity by some unknown and uncompensated amount, which can be determined by letting the battery stabilize and remeasuring the specific gravity.*

Figure 9: Time Required for SG to Stabilize During Discharge Rest Intervals

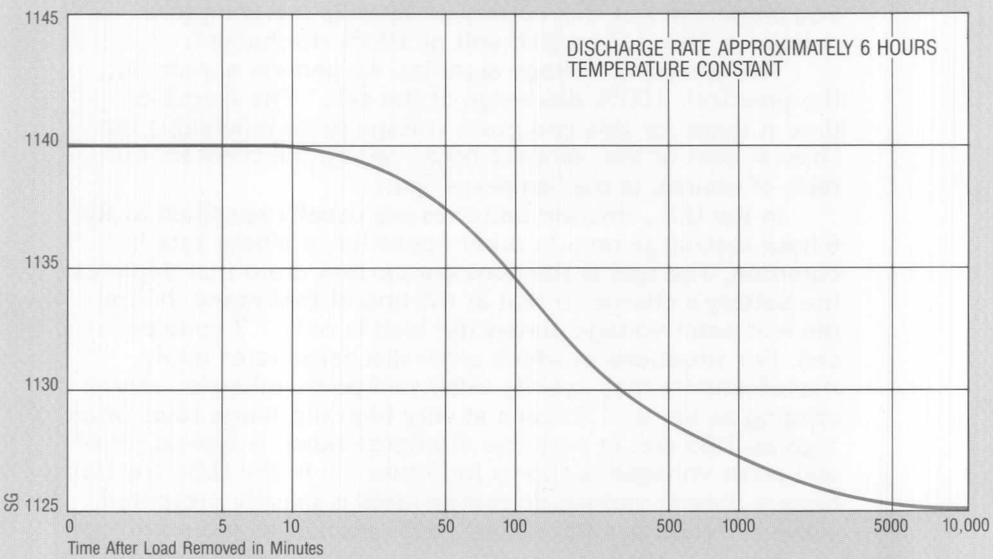
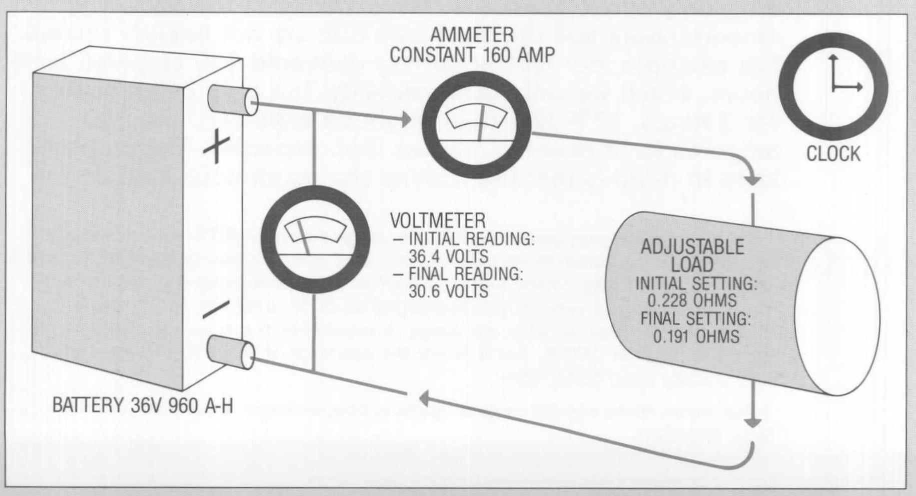


Figure 10: A Conventional Test Setup for Determining Battery Capacity



resistance is continued until the battery output voltage reaches 1.7 volts per cell (load resistance of 0.19 ohms at 160 amperes). For this battery of 18 cells the end point voltage is 18 x 1.7 or 30.6 volt at 100% discharged.

The end point voltage signifies, by general agreement, the practical, 100% discharge of the cell.* The length of time it takes for this end point voltage to be reached is the "hours" part of the "ampere-hour" rating; the constant current, of course, is the "amperes" part.

In the U.S., traction batteries are usually specified at the 6-hour discharge rate. In other countries, a 5-hour rate is common. The rate is the constant current drain that depletes the battery's charge so that at the end of that many hours, the end point voltage across the load is only 1.7 volts per cell. For situations in which other discharge rates apply, manufacturers may specify other end point voltages...some ranging as low as 1.2†volts at very high discharge rates or as high as 1.85 volt at very low discharge rates. A typical set of end point voltages is shown in Figure 11. In the U.S., traction battery data at various discharge rates is usually presented using 1.7 volts per cell as the 100% discharge end point.

Capacity and Discharge Rate

If we assume that the capacity of a typical 960 ampere-hour battery is unaffected by discharge rate, we would expect it to discharge in 3 hours with a current of 320 amperes (960 Ah divided by 320 A = 3 Hrs). Actually, at a current drain of 320 amperes, the final voltage of 1.7 volts per cell is reached after only about 2.5 hours. The capacity of the battery in ampere-hours and the discharge rate are not linearly related. For example, our typical battery delivered 160 amperes for 6 hours, which we call 100% capacity, but only 265 amperes for 3 hours, 17% less than might be expected, and 350 amperes for 2 hours, 27% less than expected. The point to keep in mind is that the heavier the continuous load on the

**For all practical purposes, a cell is discharged only to 80% of its capacity because energy drawn from the cell after that point causes voltage to drop at a steep and rapid rate. In the world of lead acid traction batteries and fork lift trucks, a battery is considered discharged at 80%, while at 100% discharge it is well into the area of deep discharge. It would seem prudent to simply term the 80% level as 100%, but it is not the province of this book to alter any such widely used convention.*

† For some street electric vehicle applications, voltages as low as 1.0 have been specified.

Figure 11: Typical End Point Voltage as a Function of Discharge Rate: (Valid when manufacturer rates battery with a current-dependent end point voltage, [from Manufacturers' data].)

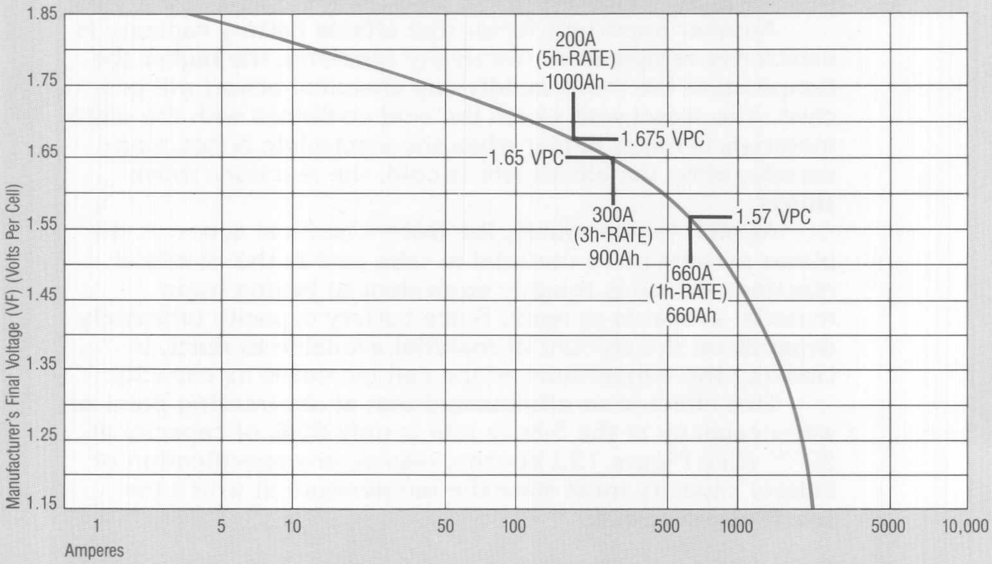
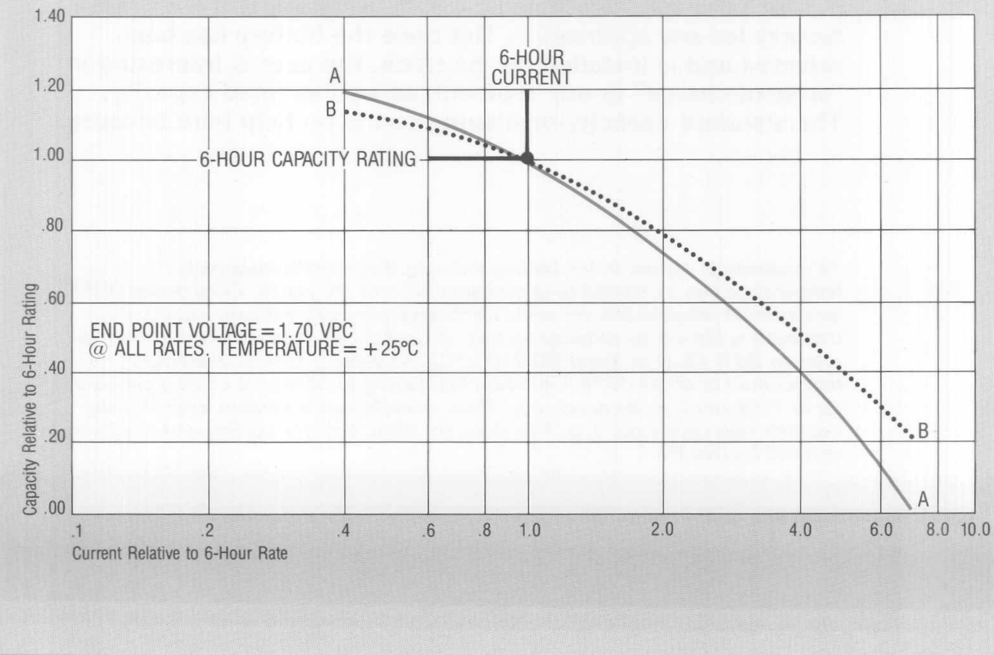


Figure 12: How Battery Capacity Varies with Discharge Rate



battery, the less capacity it has. Figure 12 shows the manner in which discharge rate affects the capacities of two similarly rated batteries from two different manufacturers.

Capacity and Temperature of Electrolyte

Another important factor that affects battery capacity is electrolyte temperature. Generally speaking, the higher the temperature the more rapidly any chemical action will proceed. The speed with which the acid combines with the plate materials is much higher when the electrolyte is hot. Conversely, when the electrolyte is cold, the reactions move slower.

At high temperatures, the faster chemical action at the plates permits more material to take part in the chemical reactions, which is roughly equivalent to having more material available to react. Since battery capacity ultimately depends on the amount of material available to react, increasing the temperature of the cell increases its capacity.*

This effect is so pronounced that at the freezing point of water,capacity at the 5-hour rate is only 65% of capacity at 80°F. (See Figure 13.) For this reason, any specification of battery capacity must state the temperature at which the specification applies.

State-of-Charge Measurements

The constant-current method outlined earlier (Figure 10) is the way in which batteries are evaluated at the factory to produce the specifications by which users select the correct battery for any application. But once the battery has been selected and is installed on the truck, the user is interested in "state-of-charge" at any moment, as well as rated capacity. The standard capacity-measuring test is no help here because

**It is generally agreed in the battery industry that continuously high temperature can be related to grid deterioration of the plates. Considering 80°F as a normal temperature, for each 15°F above normal, industry experts say that battery life will be reduced by half. A typical battery discharged at normal rates to 80% DOD at about 80°F (25°C) will show a raise of electrolyte temperature of about 12°F. To return the battery to normal, a cooling period of up to 12 hours may be necessary. Thus, manufacturers caution against using batteries two cycles per day. This does not allow time for cooling and results in reduced battery life.*

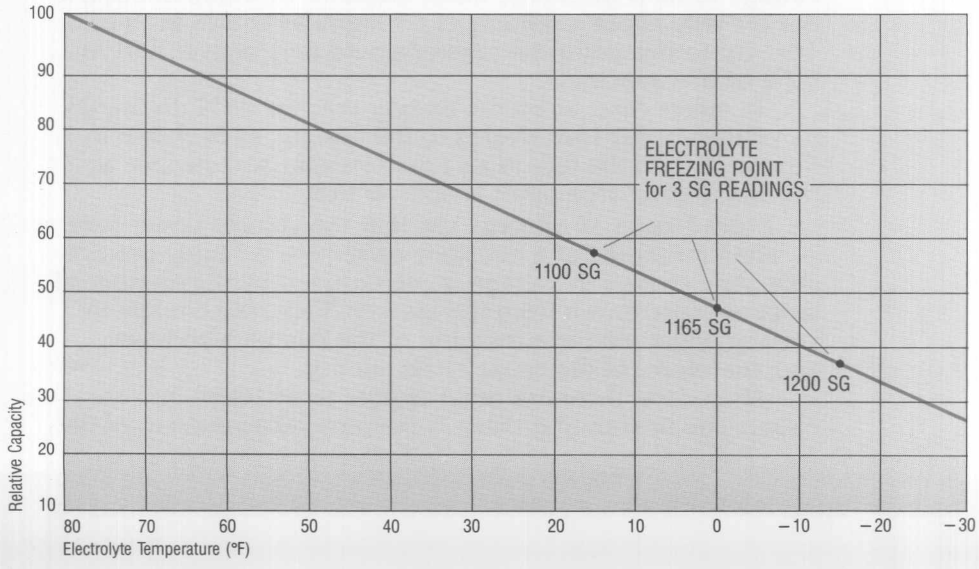
currents are constantly changing. Four techniques are used to measure state-of-charge:

- Specific gravity measurements
- Open circuit voltage measurements
- Measurement of battery voltage under load
- Ampere-hour measurements

Specific Gravity and Open Circuit Voltage

The open circuit voltage of a cell is a precise indicator of specific gravity when a cell is fully stabilized. And as such, the open circuit voltage is a precise measure of state-of-charge. Because open circuit voltage is determined solely by the concentrations of acid at the plates, it will not agree with specific gravity readings unless the acid is uniform everywhere in the cell. Then, measuring the open circuit voltage after stabilization is equivalent to measuring the specific gravity. This relationship is shown in Figure 14. The

Figure 13: How Battery Capacity may be Affected by Electrolyte Temperature.



time required for stabilization can be hours, depending on the depth and duration of discharge and is different for cells of different design. Under laboratory conditions, Figure 14 is a valuable relationship; in practical applications, however, it is ambiguous at best. The unstabilized open circuit voltage will always read higher than at the equivalent point in Figure 14 if the cell has just been taken off the charger. Conversely, the unstabilized open circuit voltage will always be lower than at the equivalent point in Figure 14 if the cell has recently been discharged.

Figure 15 shows open circuit voltage of a typical cell measured at various times after disconnecting the load. In this test, the open circuit voltage rose rapidly but did not reach its stable value of 1.982 volts until more than 100 hours had elapsed. The peak of 1.990 volts reached after some 6 hours was not sustained.

Voltage under Load

Under test conditions like those shown in Figure 10, we can examine the way voltage under load is related to battery capacity. For example, let's assume that we are testing a traction battery with a capacity of 1050 Ah at the 6 hour rate.

At a moderate load of 200 amperes, we find that the voltage stays constant (within about 7%) for nearly 4 hours (actually 3.96 hours, as shown in Figure 16). Up to this point the battery has delivered 792 Ah, or 80% of its capacity.

If we repeat the test, but draw 400 amperes, the nominal voltage to 80% discharge holds constant to within about 8%, but for only about 1.6 hours (1.57 hours as shown in Figure 16). Up to this point the battery would only deliver 628 Ah, 80% of its capacity.

In either case, when the battery reaches 80% discharge, its voltage under load begins to fall rapidly, as is shown in Figure 16, and the fall-off rate gets steeper and steeper as the 100% discharge point is approached.

From Figure 16 you can see that the voltage under load — when measured at a constant current — is highly predictable. Any change in voltage is determined by the number of ampere-hours drawn from the battery. Thus, the change in voltage under load is a measure of the charge withdrawn and, therefore, of the capacity remaining.

Of course, there are other factors to be taken into account. The first among these is that any measurement of bat-

Figure 14: How Stabilized Open Circuit Voltage Reflects Stabilized SG

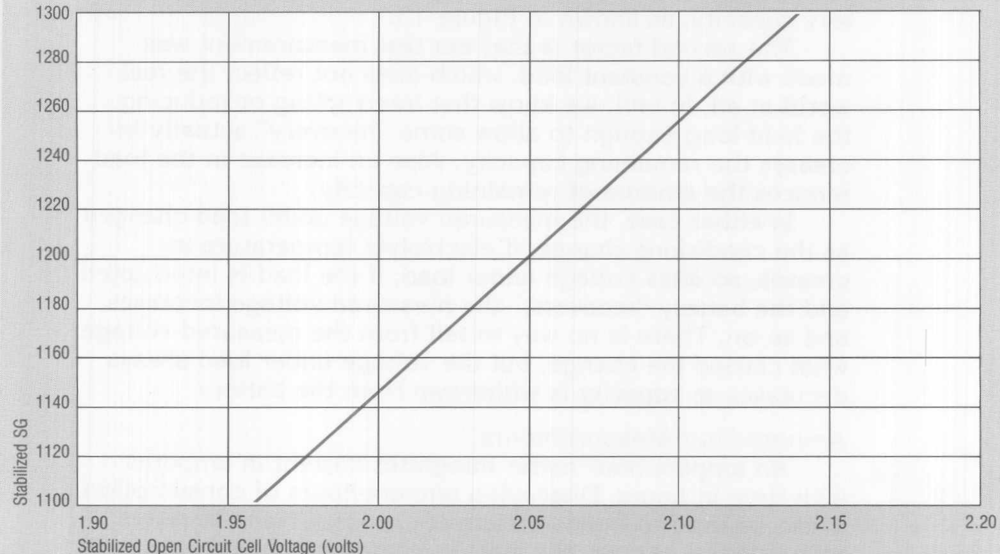
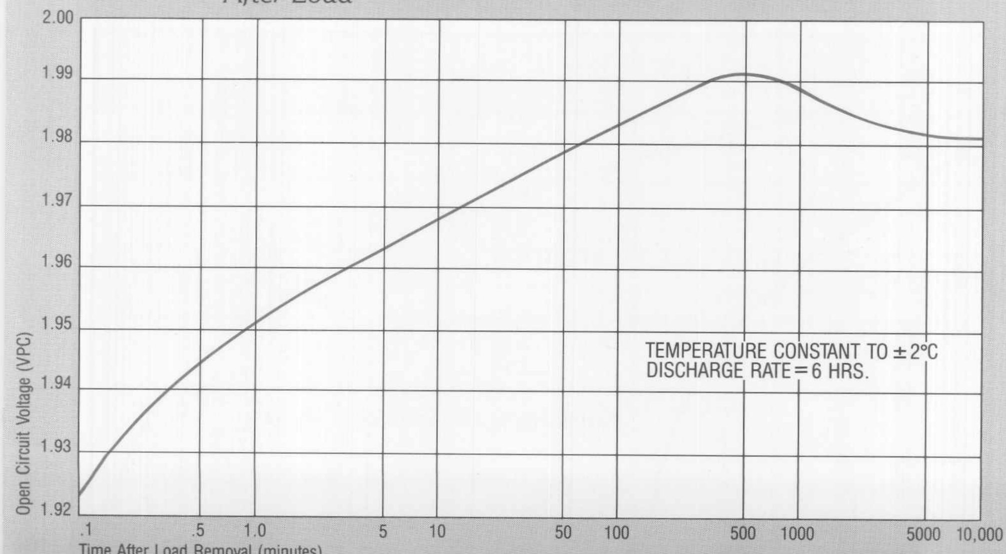


Figure 15: Variation of Open Circuit Voltages as Cell Recovers After Load



tery characteristics is highly dependent on electrolyte temperature. The higher the temperature the greater the battery capacity, as shown in Figure 13.

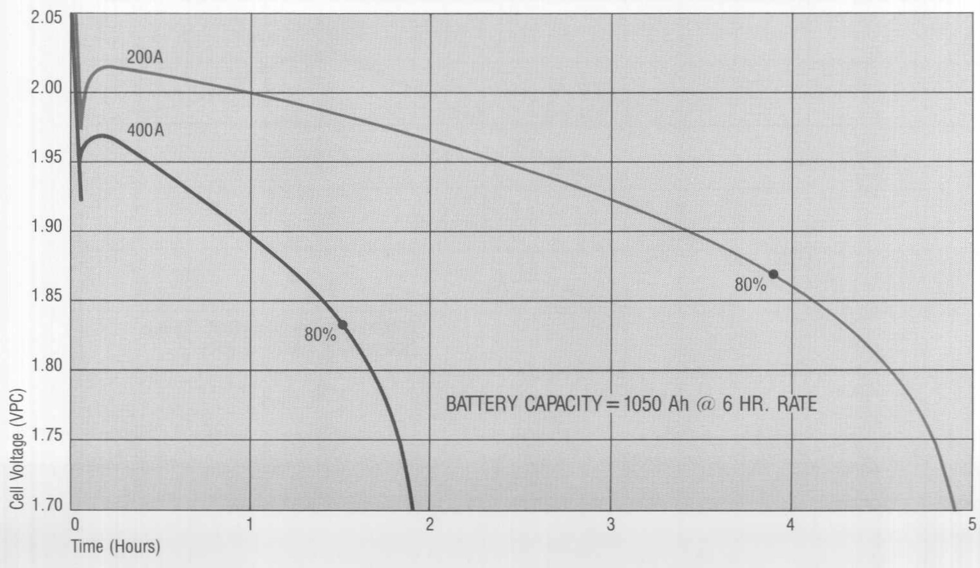
The second factor is that our test measurement was made with a constant load, which does not reflect the real world at all. In fact, we know that interrupting or reducing the load long enough to allow some "recovery" actually increases the remaining capacity. Also an increase in the load reduces the amount of remaining capacity.

In either case, the measured voltage under load changes as the conditions change. If electrolyte temperature increases, so does voltage under load; if the load is interrupted and the battery "recovers," the measured voltage increases, and so on. There is no way to tell from the measured voltage what caused the change, but the voltage under load always decreases as capacity is withdrawn from the battery.

Ampere-hour Measurements

An ampere-hour meter integrates current in amperes with time in hours. Displaying ampere-hours of consumption, it can be used to indicate state-of-charge. Given the rated capacity of a battery, the state-of-charge can be calculated by subtracting ampere-hours consumed from rated capacity. This can be done by the Ah instrument and displayed directly as state-of-charge.

Figure 16: Cell Voltage at Two Constant Currents



Section 3.

BATTERY CHARGING

Introduction

A lead-acid battery can be discharged and recharged many times. In each cycle, the charging process stores energy in the battery in the form of potentially reactive compounds of sulfuric acid, lead and lead oxide. The discharge process is another chemical reaction among those components that release the stored charge in electrical form. Since no chemical or physical process can ever be 100% efficient, more energy is always used to charge the battery than can be recovered from it. Thus, determining the optimum conditions for battery charging grows in importance as the cost of energy increases.

How Energy Is Stored in the Cell

Forcing a direct current into the cell in the reverse direction replaces energy drawn from the cell during discharge. The effect on the electrolyte and the plates during this charging process is essentially the reverse of the discharge process. Lead sulfate at the plates and the water in the electrolyte are broken down into metallic lead, lead dioxide, hydrogen and sulfate ions. This re-creation of plate materials and sulfuric acid restores the original chemical conditions including, in time, the original specific gravity.

The amount of energy it takes to re-create the original specific gravity is, of course, at least the same as the energy produced by the chemical reactions during discharge. This energy is supplied by the charger in the same form that it was removed from the battery: as volts and ampere-hours (or kilowatt-hours). Thus, if the battery produced 36 kilowatt-hours during discharge, it takes at least 36 kilowatt-hours to recharge it, plus additional kilowatt-hours to make up for losses in the energy-transfer processes.

During the first few hours that an 80% discharged battery is on the charger, the charging current is relatively high. For example, in the first four hours of charging, about 70% of the ampere-hours previously withdrawn from the battery has been restored. (See Figure 17.) For the next three hours, as battery voltage approaches the charging voltage, the charging current through the electrolyte gradually decreases, so that from the end of the fourth hour until the end of the seventh, the state-of-charge increases by about 30%.

At this point, the number of ampere-hours returned to the battery is about the same as the number withdrawn, but the battery will still accept additional ampere-hours up to about 105% of the number withdrawn. Beyond about 105%

(the nominal value for a "strong" battery) virtually all ampere-hours supplied to the battery are consumed in electrolysis and in heating the electrolyte. However, up to about this point the added ampere-hours serve mainly to make up for internal "coulombic" inefficiences.

For the charge cycle as for the discharge cycle, stabilized specific gravity is a measure of the state-of-charge. Also, as during discharge, specific gravity does not respond instantly throughout the electrolyte. Instead, the specific gravity is highest at the plates, where sulfate ions are released and the greatest number of them are concentrated. Farther from the plates, specific gravity remains lower until the freed sulfate ions have diffused evenly throughout the electrolyte.

Specific gravity, therefore, lags well behind the state-of-charge of the battery, as shown in Figure 18. The maximum specific gravity lag is considerably greater in the charging process than in discharging. Starting at approximately 1140 SG (for a typical 80% discharged cell), after an hour on charge, the specific gravity rises 4 "points," only 3% of the total rise of 150 points. But nearly 20% of the ampere-hours have been returned to the battery in that same hour.

By the end of the third hour, specific gravity has risen only a total of 32 points, to 1172 SG, or 21% of the total rise, yet the returned charge is now about 50%. During hours 4, 5 and 6, specific gravity begins to catch up and, at the end of the sixth hour, specific gravity is 1278 SG, or 92% of its final value, compared to a returned charge of 95%.

Battery Chargers and Charging

The basic types of battery chargers available today are motor generator, ferroresonant and pulsed. Use of the correct charger is an important factor in maximizing the overall efficiency of the battery system. Used correctly, under proper conditions, a modern battery charger will routinely provide overall efficiencies on the order of 85% with a battery of 18-24 cells; 80% with 12 cells and 75% with a 6-cell battery.

Four methods exist to control the DC current and voltage supplied to a battery in the charging process: two-rate; voltage detect and time; taper; and pulsed.

In the two-rate method, charging begins at a high rate that is dropped to a much lower rate after 80-85% of the ampere-hours have been returned to the battery. This lower

Figure 17. How Ampere-Hours Are Returned to the Battery During an 8-Hour Charge

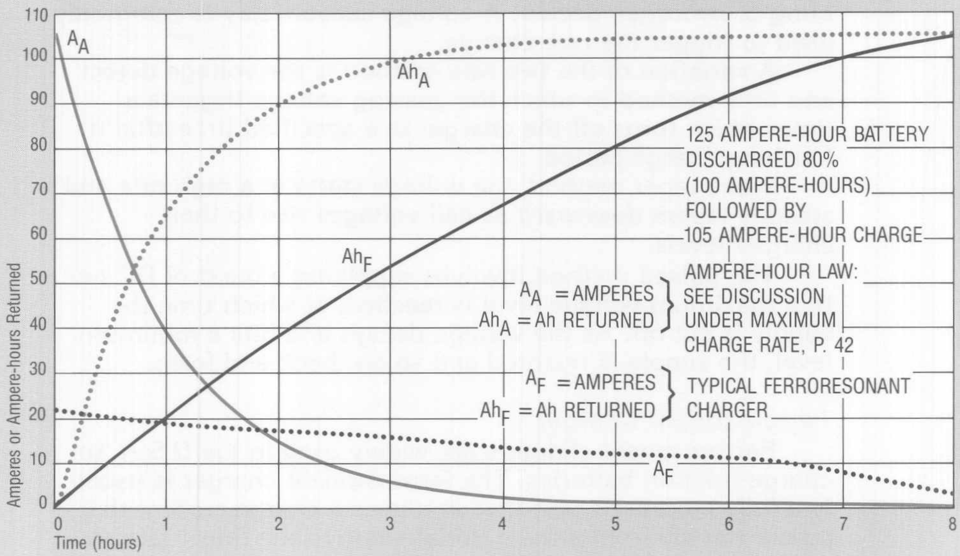
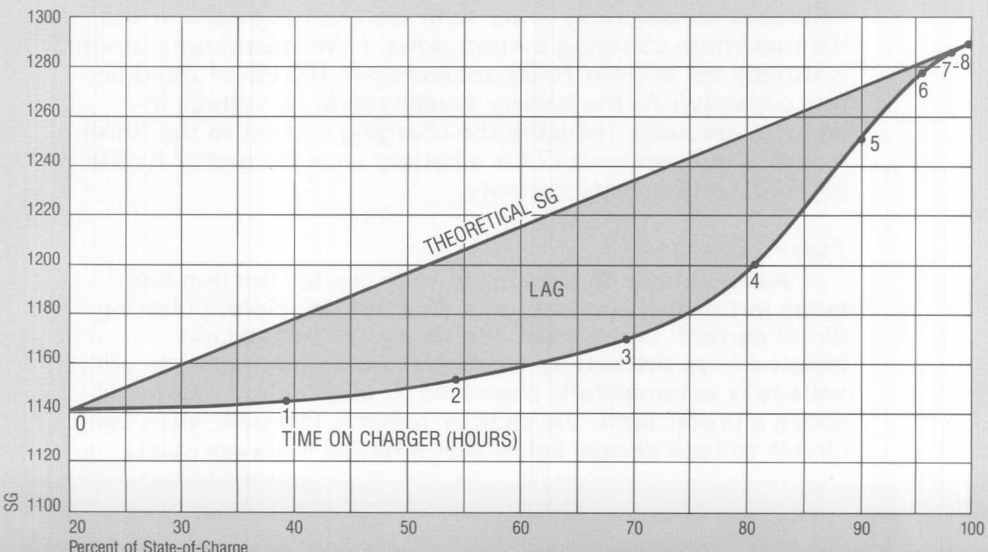


Figure 18. Lag of SG Measured During Charging Process Against Theoretical SG vs State-of-Charge



rate then tapers to a finish rate. The rate-change point coincides with the electrolyte's gassing voltage, at which bubbling of hydrogen occurs. A voltage sensor/relay is commonly used to trigger the rate change.

A variation of the two-rate method is the voltage detect and time method in which the gassing voltage triggers a timer which turns off the charger in a specified time after a finishing charge period.

In the taper method, the voltage starts at a high rate and steadily tapers downward as cell voltages rise to their charged levels.

The pulsed method involves supplying a burst of DC until a maximum voltage level is reached, at which time the supply is cut off. As the voltage decays and hits a minimum level, the supply is restored and so on, back and forth.

Ferroresonant Charger

Ferroresonant chargers are widely used in the U.S.A. to charge traction batteries. The ferroresonant charger is usually a fully automatic unit that produces a charge current that tapers steeply from a large initial value to the finish rate. A typical ferroresonant charger produces a current-voltage pattern like the one shown in Figure 19.

The internal voltage of the ferroresonant charger is essentially constant throughout the charge period, usually 8 hours. The output current, however, is limited by the battery voltage. At the beginning of the charge period, the battery voltage is considerably lower than the charging voltage and the maximum charging current flows. (This maximum current is usually set at from 16-26 amperes per 100 Ah of rated battery capacity.) As the battery is recharged, its voltage increases, gradually reducing the charging current to the finish rate of 2 to 5 amperes (7 for a battery near the end of its life) per 100 Ah of battery capacity.

Pulsed Chargers

Another type of charger, in wide use for traction batteries in Europe, operates on a different principle: pulsating direct current. In this case, the charger is periodically isolated from the battery terminals and battery open circuit voltage is automatically measured. If open circuit voltage is above a preset limit, the charger remains isolated; when open circuit voltage decays below that limit (as it always must),

Figure 19: *Current Voltage Relationships in a Ferroresonant Charger*

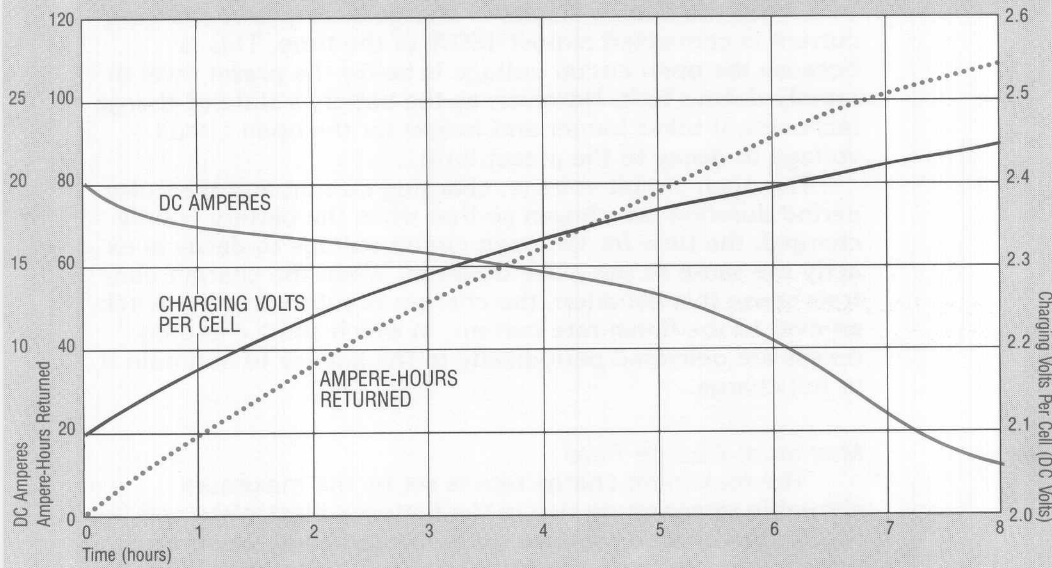
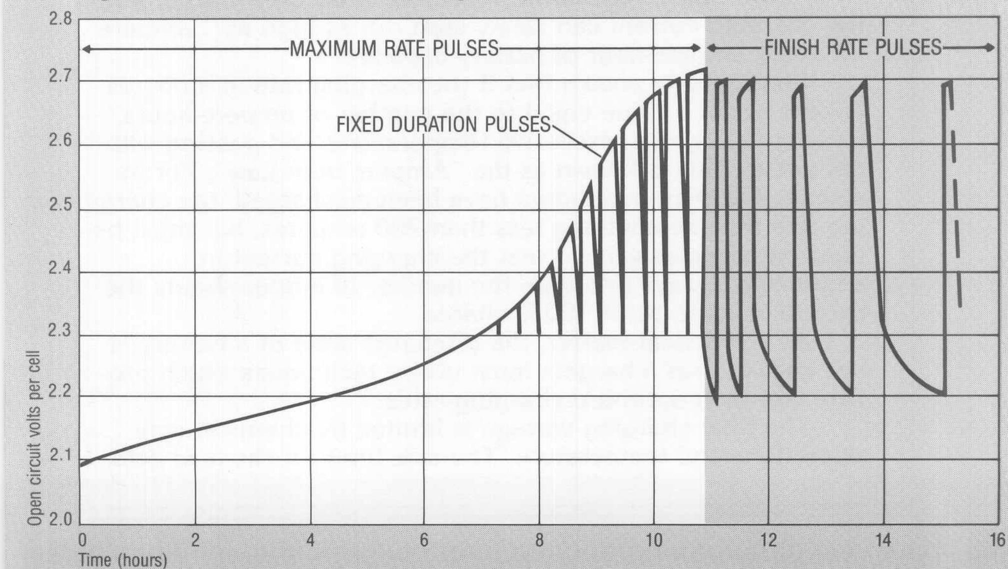


Figure 20: *How a Pulsed Charger Operates*



the charger is reconnected for another period of equal duration. Figure 20 shows this procedure.

When the battery's state-of-charge is very low, charging current is connected almost 100% of the time. This is because the open circuit voltage is below the preset level or rapidly decays to it. However, as the battery's state-of-charge increases, it takes longer and longer for the open circuit voltage to decay to the preset limit.

The open circuit voltage, charging current and the pulse period duration are chosen so that when the battery is fully charged, the time for the open circuit voltage to decay is exactly the same as the pulse duration. When the charger controls sense this conditon, the charger is automatically switched over to the finish rate current, in which short charging pulses are delivered periodically to the battery to maintain it at full charge.

Maximum Charge Rate

The maximum charge rate is set by the maximum allowable temperature rise in the battery's electrolyte and the requirement not to produce excessive gassing. A lead acid battery that has been normally discharged can absorb electrical energy very rapidly without overheating or excessive gassing. A practical temperature limit that is widely accepted is that the electrolyte should not rise above 46.1 °C (115 °F) with a starting electrolyte temperature of 29.4 °C (85 °F).

In the case of the battery that has been fully discharged, the charging current can safely start out as high as 1 ampere for every ampere-hour of battery capacity.

Studies have shown that if the charging rate in amperes is kept below a value equal to the number of ampere-hours lacking full charge, excessive temperatures and gassing will not occur. This is known as the "Ampere-hour Law". For instance, if 200 ampere-hours have been discharged, the charging rate may be anything less than 200 amperes, but must be reduced progressively so that the charging current in amperes is always less than the number of ampere-hours the battery lacks to be at 100% charge.

As a practical matter, the discharge state of a battery is not known; thus, chargers must utilize techniques which provide less than optimum charging rates.

The final charging voltage is limited by chemical considerations and temperature. The safe limit for the lead acid

traction battery commonly used with fork lift trucks is generally agreed to be between about 2.40 and 2.55 volts per cell when charged at 25 °C ambient temperature.

Finish Rate

The most common finish rate is approximately 5 amperes per 100 Ah of rated capacity, a rate low enough to avoid severe overcharging but high enough to complete the charging process in the eight hours normally available.

Equalizing Charges

By maintaining the finish rate for an extended period (up to 6 hours), a battery with cells at slightly varying voltages and/or depths of discharge can be equalized. The continued input of charge (overcharging) to the battery serves to "boil" off water in those cells of higher voltage and/or depths of discharge. Upon completion of the process, levels must be checked and water added as required to depleted cells. New batteries, referred to as low maintenance systems, may not permit adding of water and therefore are not designed for equalizing charges.

Terminating the Charge

Overcharging can materially shorten the life of a battery, and no amount of overcharging can increase battery capacity beyond its rated value. There are several "rules of thumb" that are followed in deciding when to end the charge:

- When the charge is complete, the voltage levels off and there is no further increase
- Charge current readings level off at the finish rate
- The battery gasses freely
- The specific gravity reaches a stable value.

Gassing

Hydrogen bubbles are produced at the negative plates and oxygen at the positive plates during charging. After the battery reaches full charge almost all added energy goes into this gassing. The gassing process begins in the range of 2.30 to 2.38 volts per cell, depending on cell chemistry and construction. After full charge, gassing releases about 1 cubic foot of hydrogen per cell for each 63 ampere-hours supplied. Since a 4% concentration of hydrogen in air is explosive, ventilation of battery rooms is required for safety.

Energy Efficiency in the Charging Process

Nothing is free, least of all energy. Since the charging process can never be 100% efficient, we must be careful about how energy is used in this process.

The charging process converts energy supplied by the local utility to kilowatt-hours stored in the battery which is subsequently available for transfer to a load . . . in our use, an electric fork lift truck. Two major components are involved in this process: the battery itself and the charger. The charger interfaces with the power line on one side and with the battery on the other. The battery, in turn, interfaces with the charger on its input side and with the truck on its output side.

How the Charger Affects Energy Efficiency

Energy is consumed in the charging process. While most of the charging energy goes into restoring the original chemical conditions in the cell, some is lost in the battery, and some is lost in the charger, mainly as heat.

We define the efficiency of the charger as the efficiency with which power line energy is supplied to the battery in usable form. This efficiency varies not only from type to type and from manufacturer to manufacturer, but also may vary from unit to unit. Let's explore this with measurements in a "typical" case (charging a 36V, 1200 ampere-hour battery).

- During the typical 8-hour charging period, the charger supplies energy to the battery at a rate that depends on the battery's state-of-charge at any instant. This accumulation of energy is shown in Figure 21 as curve C. Note that this cumulative curve rises steeply and then gradually becomes flatter until at the end of 8 hours it is almost completely horizontal.
- The charger draws energy from the power line to provide the battery operating energy. This energy is shown as curve L in Figure 21. The shape of this curve is similar to that of the curve C, but L is always higher than C because the charger takes more energy from the line than it delivers to the battery.
- Working from these two curves, it is possible to determine the actual charger efficiency up to any time on charge. All we need to do is measure the heights of the two curves at the desired time mark, divide C by L, and multiply by 100. The overall charge efficiency E,

is determined by the values at the end of the 8-hour period.

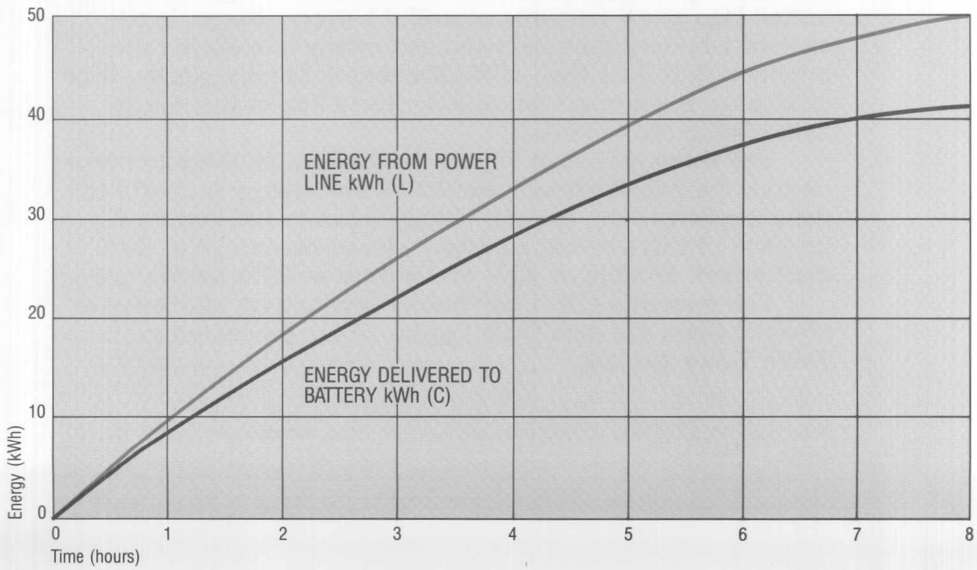
- In a typical case, the charger draws approximately 50 kilowatt-hours from the line and delivers about 42 of them to the battery, when recharging our typical battery from 80% discharge. Thus, the charger is about 84% efficient over a standard 8-hour charge period when recharging an 80% discharged battery.

How the Battery Affects Energy Efficiency

The battery accepts only part of the energy supplied by the charger; furthermore, it also delivers only part of that energy to the load. The efficiency with which the battery releases the energy supplied it by the charger can be demonstrated in a manner similar to that used to determine charger efficiency.

- During the 8-hour charge period, our typical battery accepts 42 kilowatt-hours of energy from the charger, as shown in Figure 21.
- To understand clearly the battery's efficiency as part of the total efficiency of the electric truck system, it must be remembered that the amperes are being delivered to the battery at the charger voltage which, for a typical 36 volt battery, might be an average of 40-42

Figure 21. How the Charger Affects Efficiency



volts, while the battery discharge is at an average of 33-35 volts. Even if the total ampere-hours of charge and discharge were the same (and normally we charge an additional 5%) the kilowatt-hours (which is the total energy) would vary by the difference of the average voltage during charge and the average voltage during discharge. Consequently the battery efficiency is much less than may be thought if one only considers the ampere-hours charged and discharged.

- The overall battery efficiency is determined by comparing the 32 kilowatt-hours delivered from the battery* with the 42 kilowatt-hours delivered to it: $32 \div 42 \times 100 = 76\%$.

Overall System Efficiency

The overall system efficiency is the efficiency with which the power line energy (50 kilowatt-hours) is converted to energy delivered to the load (32 kilowatt-hours): $32 \div 50 \times 100 = 64\%$. This figure duplicates the overall system efficiency calculated from the two factors, charger efficiency and battery efficiency: $84\% \times 76\% = 64\%$.

How Depth of Discharge Affects System Efficiency

Efficiency is affected by the depth of discharge of a battery when it's placed on charge. Any battery that is less than 80% discharged forces the charger to become a waster of energy. Significant amounts of power line energy are converted into small amounts of useful battery charge. In the case of a battery that has been essentially idle during the previous shift (less than 10% discharge), blindly placing it on charge for eight hours will waste nearly half of the energy delivered to the battery.

The three graphs of Figure 22 show, in an 8-hour charge period, the hour-by-hour cumulative line energy input (L) to the charger and the charger energy input to the battery (C) for each of three cases: a battery placed on charge at 80% discharged; another at 40% and a third at 20% discharged.

The dramatic effect on charger and battery efficiency is obvious when the data from Figure 22 are presented in Table 1 and Table 2.

**Battery output (kWh) equals average voltage times Ah delivered to 80% DOD.*

Figure 22: Effect of Depth of Discharge (DOD) on System Efficiency

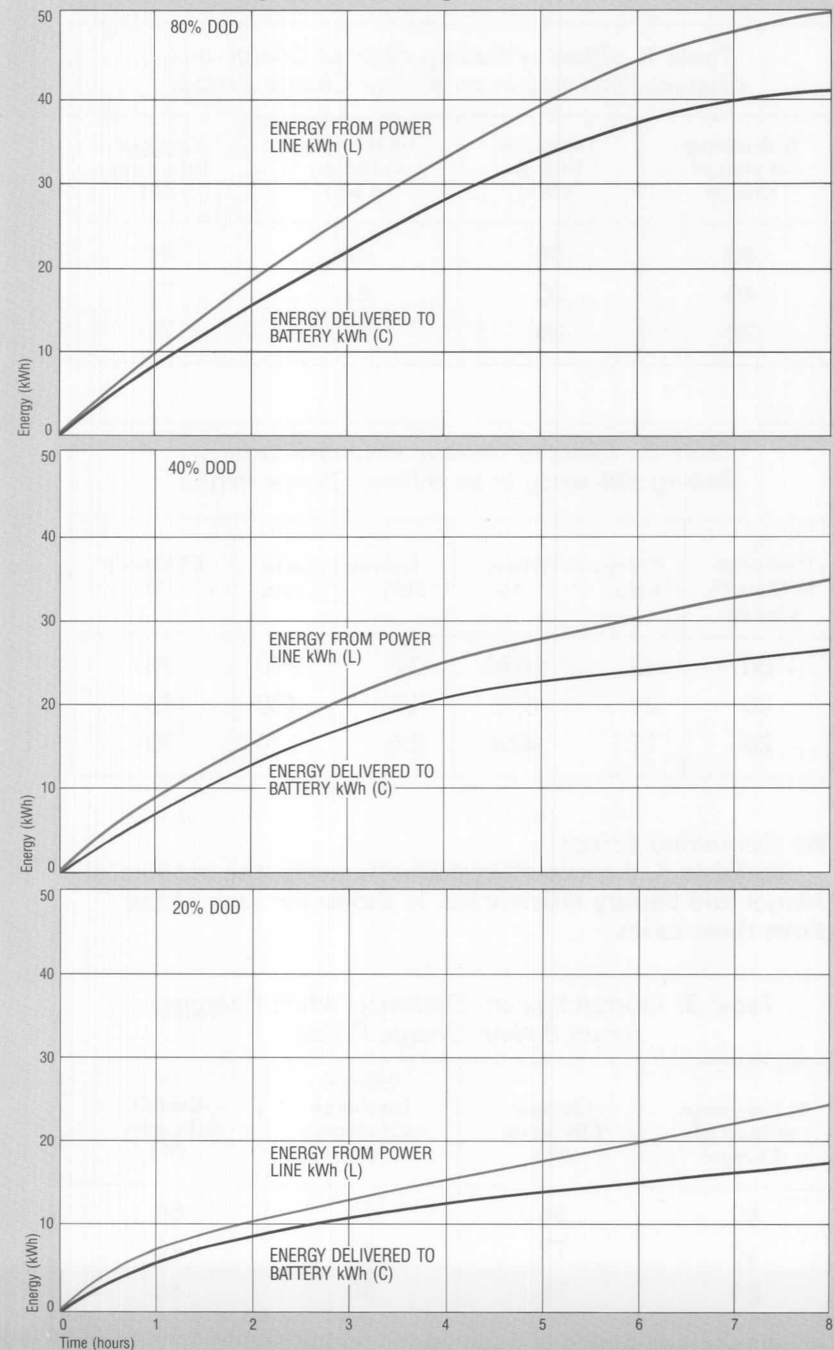


Table 1: Effect of Battery State-of-Charge on Charger Efficiency in an 8-Hour Charge Period.			
% Discharge at start of Charge	Total Line Energy (kWh)	Total Energy to Battery (kWh)	Charger Efficiency (%)
80	50	42	84
40	35	27	77
20	24	17	71

Table 2: Effect of Battery State-of-Charge on Battery Efficiency in an 8-Hour Charge Period					
% Discharge at Start of Charge	Energy to Battery		Energy to Load		Efficiency %
	kWh	Ah	kWh	Ah	
80	42	1030	32	960	76
40	27	652	17	480	63
20	17	424	8.6	120	50

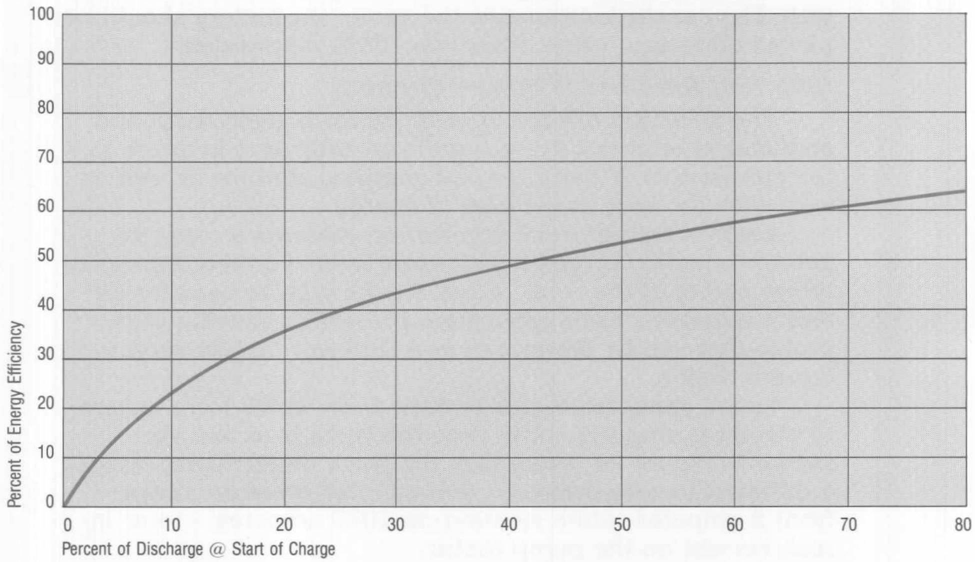
The Combined Effect

In Table 3, the overall system efficiency, the product of charger and battery efficiencies, is shown for each of the above three cases.

Table 3: Overall System Efficiency When Charging for an 8-Hour Charge Period			
% Discharge at Start of Charge	Charger Efficiency (%)	Charge/ Discharge Efficiency (%)	Overall Efficiency (%)
80	84	76	64
40	77	63	49
20	71	50	36

From this examination, it becomes quite clear that if a fixed, 8-hour charging routine is to be followed, the overall efficiency with which energy is used is determined mostly by the state-of-charge of the battery when it goes to the charger as shown in Figure 23.

Figure 23. Overall Energy Efficiency in Charging a Battery Discharged to Various Depths (8-Hour Charge)



Section 4.

OPTIMIZING ENERGY USAGE

Beginning with Conclusions

After only a brief study of Figure 23, it appears that the optimum battery selection is one that results in 80% discharge by the end of a pre-established work program. Said another way, the battery should have a rated capacity of 125% of the energy it is expected to deliver during discharge. It makes no difference whether the intention is to charge the battery at the end of each workshift or whether the battery is to be charged at the completion of a particular task. The conclusion remains the same: the battery should be placed on charge when it has been 80% discharged.

Selecting the Correct Battery Capacity

The selection of battery capacity for a given truck and application becomes more significant with each increase in the capital cost of batteries and charging stations as well as with each increase in the cost of energy.

Each industrial truck application presents a separate battery-selection problem with more involved than the size or lifting ability of the truck. Since trucks may be used for different purposes, each application presents a specific work profile that can be thought of as a series of rapidly varying current drains.

In any application, this battery drain varies from instant to instant during the entire time the truck is in use. As shown in Figure 24, every task the truck performs represents a different battery drain . . . that can, for example, range from 5 amperes, while steering, to 1000 amperes, motor in-rush current on the pump motor.

Figure 25 shows a hypothetical operation for a typical truck—lifting loads and transferring them to nearby locations. Our typical truck takes 6 separate steps to complete these operations, and each step drains energy from the battery.

Of course, there is no simple way to calculate in advance exactly how much energy will be needed to perform any single step of an operation, let alone a whole day's work. The only real solution is to measure the number of ampere-hours used by the truck when it performs each step. This is done with an ampere-hour meter installed on the truck.*

With the Power Prover Ampere-Hour Meter® installed on the test truck, the driver performs the stipulated sequence of steps and the meter readings show the total ampere-hours

**The Curtis Model 1020 Power Prover® Ampere-Hour Meter is an accurate, easy-to-install ampere-hour meter widely used for this purpose.*

and the amperes used in the operation. The number used in each step of the operation can be monitored by recording the meter readings while the truck operates.

A procedure of this kind that includes representative operations performed by the truck provides a simple and accurate basis for selecting battery capacity . . . or for verifying assumptions about ampere-hour requirements.

Ways to Measure State-of-Charge on the Fork Lift Truck

The reason for measuring the state-of-charge as the battery is in use is twofold: to protect the battery from deeply discharging and, thereby, internal damage; and to protect the truck's electrical components from the negative effects of low voltages, a consequence of deeply discharged batteries. At average discharge rates of 8 hours or less, a measurement which accounts for the remaining capacity as a function of discharge rate can serve to protect both the battery and the truck.

An ampere-hour meter provides useful information that greatly simplifies specifying the correct battery and measures ampere-hours used, but not the rate at which it is used. And the rate at which it is used is crucial in measuring the state-of-charge because battery capacity is different at different rates of discharge.

Aside from ampere-hour metering, three basic measures have been used in industry to determine battery state-of-charge: specific gravity, open circuit voltage, voltage under load.

Specific Gravity: A Static Measure

Not only are specific gravity measurements not convenient to make during the work period, but their value is limited because it takes time for the specific gravity to stabilize after the battery load is disconnected. Although a convenient measure of overall battery condition, specific gravity measurements give no valid indication of the discharge history that produced the reading. Any given reading of stabilized specific gravity can either be the result of heavy discharge for a short period or of prolonged discharge at a very light load. This effect is shown in Figure 26, in which the specific gravity and the open circuit are plotted against % of discharge for currents from 25 amperes to 800 amperes for a 1200 ampere-hour battery rated at 6 hours. Any specific gravity line, for example, 1165 SG,

Figure 24: Relative Current Drain for Typical Industrial Trucks

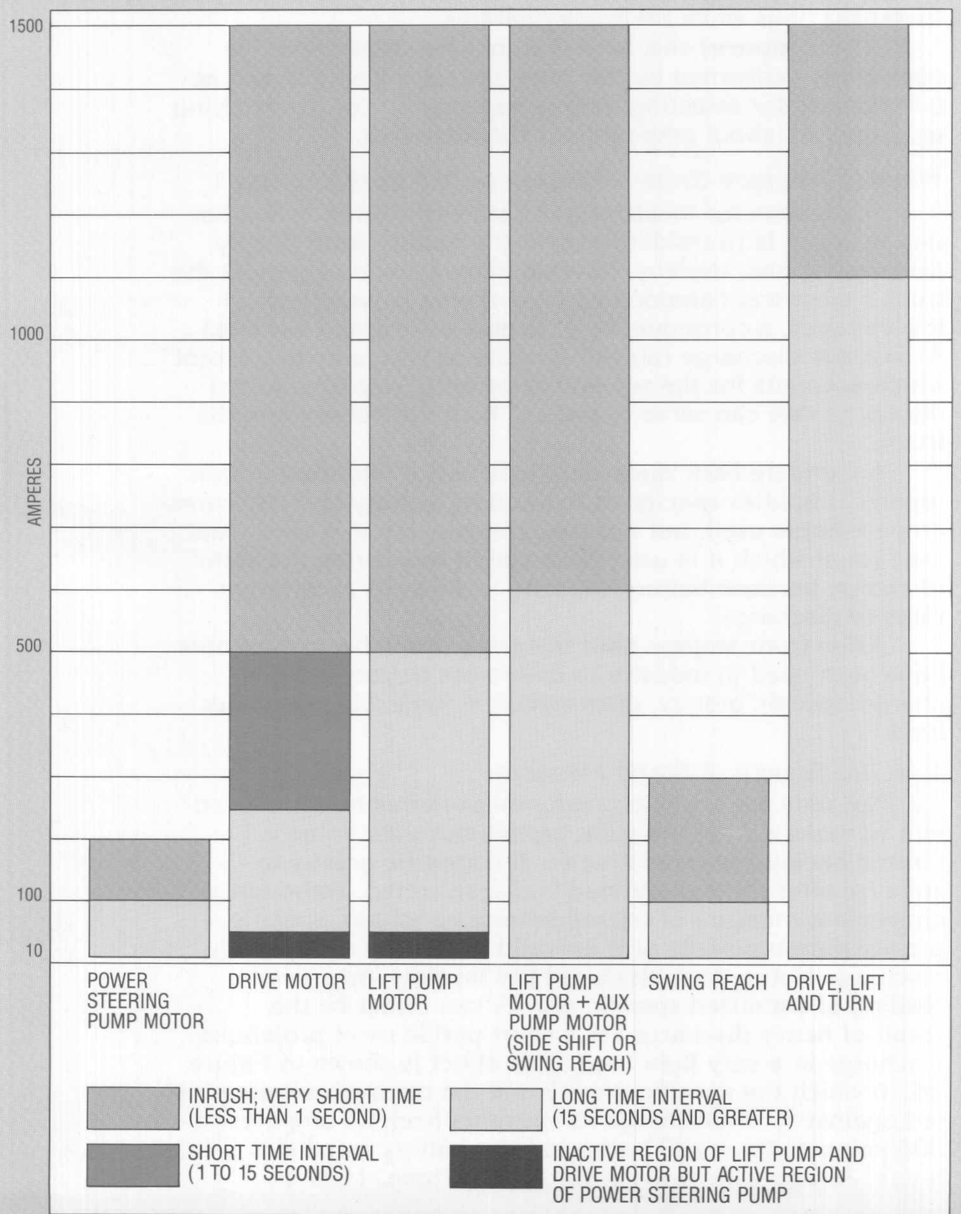
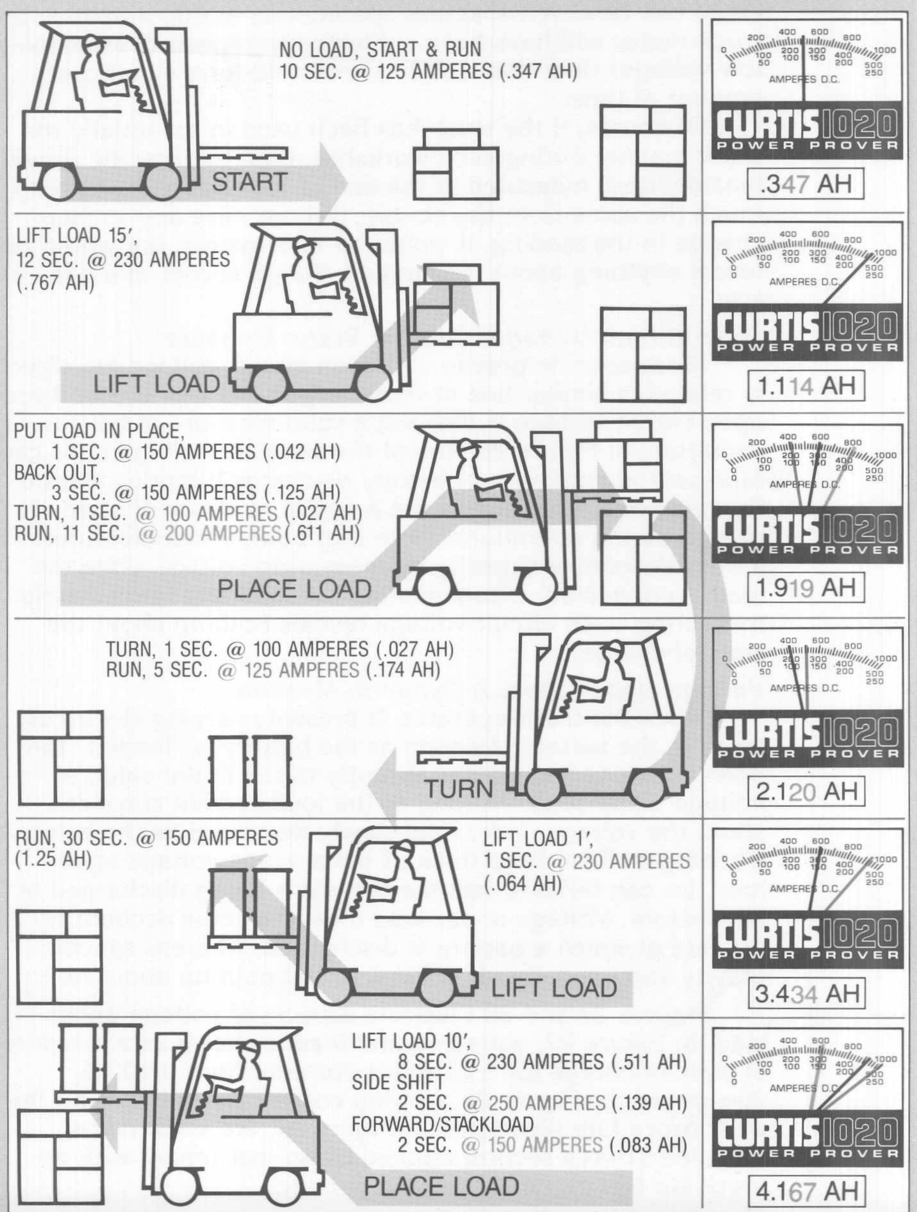


Figure 25: A Hypothetical Industrial Truck Operation



intersects a number of discharge lines. 1165 SG, in particular, corresponds to 80% discharge at the 6-hour rate (200 amperes). However, if actual operation is at 600 amperes, the truck motor will have been subjected to repeated, excessively low voltages (less than 1.7 volts per cell) for a significant amount of time.

Of course, if the truck has been used in essentially the same manner during each workshift, then the specific gravity (unstabilized) measured at the end of the shift will be pretty much the same from day-to-day. If there were any sudden change in the reading, it would be informative, but would not reveal anything about the state-of-charge except in a general way.

Open Circuit Voltage: Another Static Measure

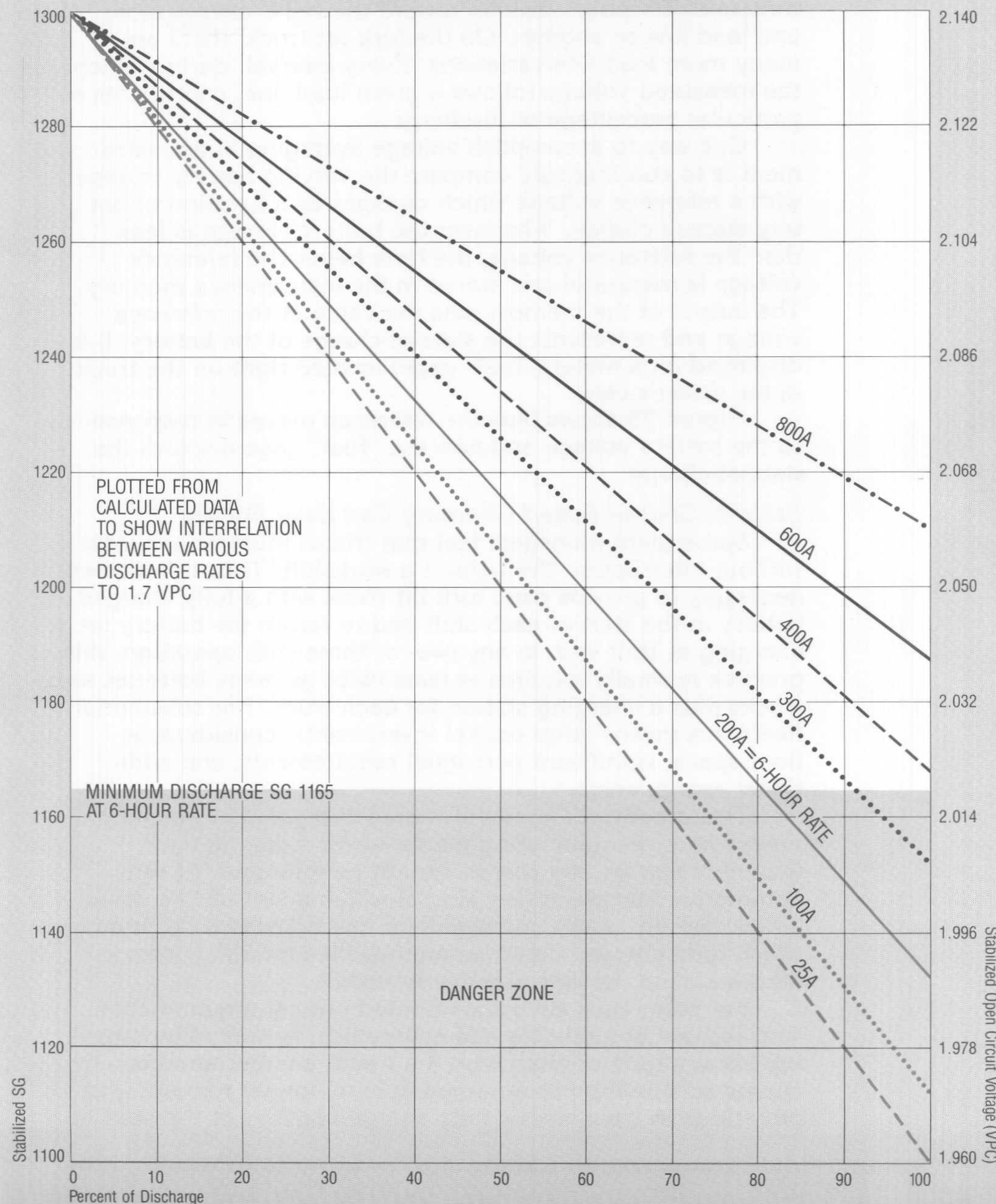
Since specific gravity and open circuit voltage are directly related, a similar line of reasoning shows that unstabilized open circuit voltage is also not a valid measure of battery condition. In Figure 26, any of the constant voltage lines can represent any number of battery discharge histories. Hence the open circuit voltage is not a useful measure of state-of-charge during operations. Note that battery manufacturers always determine capacity by measuring voltage while the load is connected. Disconnecting the load and immediately measuring open circuit voltage reveals nothing about the state-of-charge.

Voltage Under Load: A Dynamic Measure

When the truck operates, it presents varying electrical loads to the battery. As soon as the battery is "loaded" the open circuit voltage drops abruptly to the initial value of voltage under load. As long as the load current stays constant, the voltage under load slowly decreases as the battery discharges. If we keep track of the average voltage under load, we can tell how fast the battery is being discharged at any instant. Voltage under load measurements account for the rate at which a battery is discharged, whereas specific gravity and open circuit voltage reveal nothing about rate.

Figures 27 and 28 illustrate aspects of voltage under load. In Figure 27, voltage under load is shown as a measure of state-of-charge for 5 constant currents from 0-100% discharged. In Figure 28, varying current rates, based on the work procedure illustrated in Figure 24, are shown as a magnified micro-section tracked by an instrument with appropriate electronic computing circuitry.

Figure 26: *Stabilized SG and Open Circuit Voltage as Measures of State-of-Charge for Various Discharge Rates*



Since time always moves from left to right in Figure 27, the net effect of many different loads is to move the measurement point steadily toward the right, always along one load line or another. On the fork lift truck, there are many more load line variations. Every interval, during which the measured voltage follows a given load line, contributes a particular percentage of discharge.

One way to accomplish voltage averaging in an instrument is to continuously compare the varying battery voltage with a reference voltage which changes as a function of battery state-of-charge. Whenever the battery voltage is less than the reference voltage, the time below the reference voltage is measured and stored in the instrument's memory. The output of the memory sets the value of the reference voltage and represents the state-of-charge of the battery. It is displayed on a meter ("fuel" gage) located right on the truck in the driver's view.

Figure 28 shows how the reference moves in response to the battery voltage and how the "fuel" gage displays the state-of-charge.

State-of-Charge-Based Charging Can Save Energy

Some plant managers feel that trucks must be available without interruption throughout a workshift. Thus it becomes necessary to provide each fork lift truck with a fully charged battery at the start of each shift and to return the battery for charging at shift end. In any two- or three-shift operation, this practice normally requires at least twice as many batteries as trucks plus a charging station for each truck. For substantial fleets this means large capital investments, considerable floor space, significant personnel requirements, and additional energy costs.

This practice of workshift-based charging is especially prevalent in manufacturing plants where stopping the assembly line for any reason cannot be tolerated. At one automotive manufacturing site, at which a stalled line would be excessively costly, management has initiated a program in which fully charged batteries are installed on 150 trucks in 40 minutes at the end of every workshift.

For other than such above noted critical requirements, with the use of a reliable and economical means of monitoring battery state-of-charge on the truck, another approach to charge scheduling has emerged. It is no longer necessary to provide each truck with a fully charged battery at the start of

Figure 27: Voltage Under Load as the Measure of State-of-Charge

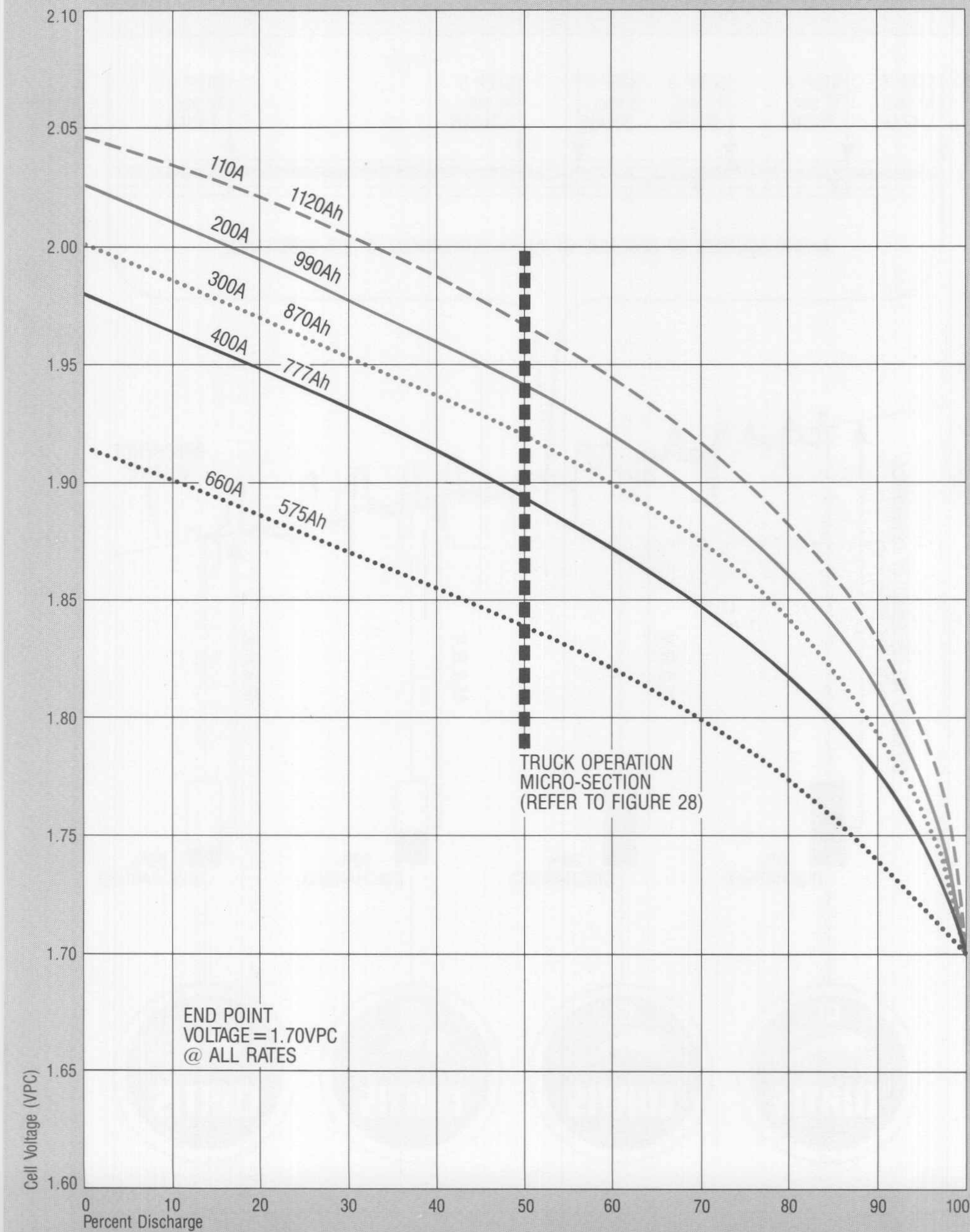
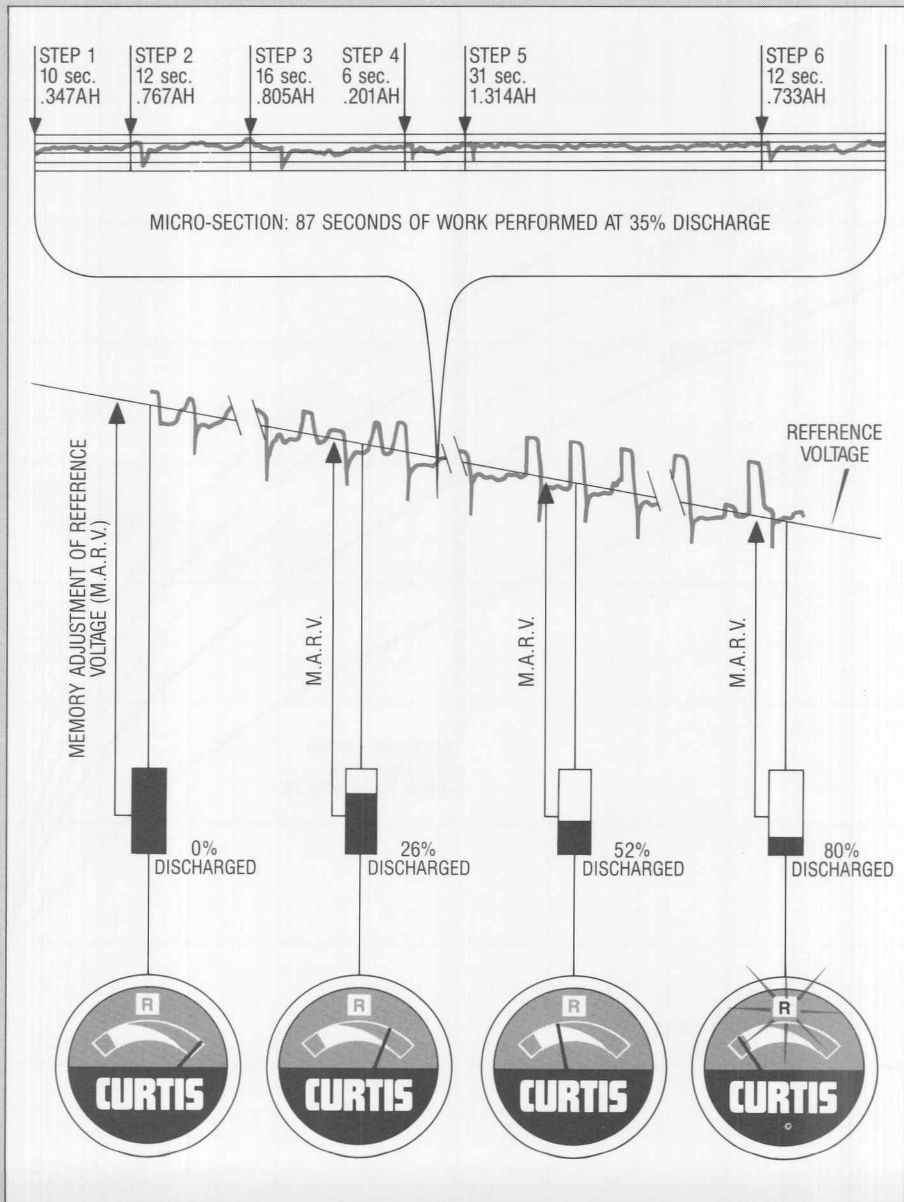


Figure 28: A Practical Application of Voltage Under Load as a Measure of State-of-Charge

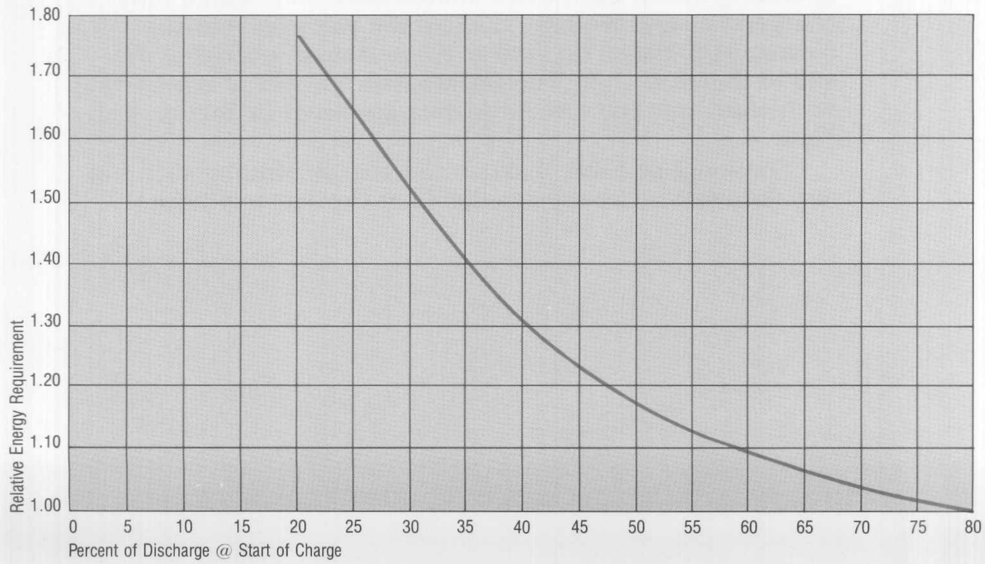


each shift and to work the battery through to shift end. Rather, if there is still significant charge left in the battery at the end of the shift, the battery can be left on the truck and worked until the need for charging is indicated. Then, and only then, the truck returns for a freshly charged battery. Its discharged battery is then placed on charge and, 8 hours later, is ready for use again.

As shown earlier, if an 8-hour charge period is used (as is generally the case), the optimum discharge point is 80%. Figure 29 shows how rapidly the energy requirements rise when batteries are charged for 8 hours after having been discharged less than 80%. Working each battery to the 80% discharge point before returning it for charging permits the most effective use of energy in the system and provides significant savings in energy costs.

Since each of the batteries reaches the 80% discharge point at a time that depends on the way it is worked, most will work longer than one 8-hour shift. Since a new battery isn't required for each truck at the end of every shift, it isn't necessary to have at least one replacement battery per truck, nor is it necessary to have at least one charger for each truck. Fewer batteries and chargers mean less capital investment, less space used for charging, and fewer people to do the work.

Figure 29: How Energy Requirements are Affected by Depth of Discharge



Further, when a battery is placed on charge it draws maximum current from the line. Placing all of the fleet's batteries on charge at one time, therefore, creates a large demand, which is reflected in the cost of energy in the form of higher utility peak demand charges. However, starting batteries on charge at different times throughout the entire shift reduces this demand and, therefore, the cost of energy.

How A "Typical" Fleet Can Save Energy

To dramatize the energy saved by charging batteries under optimum conditions, we have prepared data for a hypothetical 20-truck fleet operating for a 5-day week of 2 shifts per day. The data cover one month of 20 working days and show the following:

- That it is possible to significantly reduce the amount of energy required to operate the fleet
- That by appropriate fleet management it is possible to greatly reduce the magnitude of peak power demand
- That this modified fleet operation holds the promise of reducing the capital and labor costs associated with industrial trucks.

Our data and calculations are not derived from operating a real fleet. They do, however, suggest how to reduce the cost of operation of any real fleet of trucks.

In this fleet, all trucks are equipped with the same battery type: a 36 volt, 1200 ampere-hour unit. In the original operating mode, each truck started each shift with a fully charged battery. We have divided the batteries into six classes (*A-F*) based on their average state-of-charge at the end of a typical shift. The classes, the number of batteries in each class, and the discharge data are listed in Section I of Table 4.

Section 2 of Table 4 shows the energy used by each battery (kilowatt-hours are calculated at the average output

Table 4: Energy Usage Data for a Hypothetical 20-Truck, 2-Shift Fleet

SECTION 1 Fleet Composition		SECTION 2 Battery Data			SECTION 3 Fleet/Shift Data			
Class & Number of Trucks	Average % D.O.D. at Shift End	Output to Load Ah	Output to Load kWh	Power Line Input to Charger (kWh)	Output to Load Ah	Output to Load kWh	Power Line Input to Charger (kWh)	Overall Efficiency (%)
A-1	80.0	960	33.6	50.2	960	33.6	50.2	67
B-2	69.3	832	29.2	46.6	1664	58.4	93.2	63
C-3	58.7	704	24.9	42.8	2112	74.7	128.4	58
D-8	48.0	576	20.5	38.5	4608	164.0	308.0	53
E-4	42.7	512	18.2	36.0	2048	72.8	144.0	51
F-2	37.3	448	16.0	33.3	896	32.0	66.6	48
Fleet Totals Per Shift					12,288	435.5	790.4	55
Per Month (40 shifts)					491,520	17,420	31,616	55

voltage). Section 3 then totals these per-battery figures by battery class. The overall efficiency is calculated by dividing the output energy (kWh) by the AC input energy and multiplying by 100. Since there are 40 shifts in our 20-day month, the totals are multiplied by 40 to obtain an estimate of energy used by the entire fleet over a full month of operation. A very substantial 31.6 megawatt-hours is used . . . but at only 55% overall efficiency to produce the required 17.4 megawatt-hours of work delivered by the batteries.

By the simple expedient of returning each truck for a fresh battery when its "fuel" gage reads between 75% and 80% discharged, we can sharply reduce this energy waste. Since overall system efficiency is 67% for batteries that are charged after being 80% discharged, we can reduce the power line energy needed for our hypothetical fleet to 25.9 megawatt-hours if each battery is 80% discharged before being recharged. This means that about 5.7 megawatt-hours can be saved each month.

*Reducing Peak Power Demand Costs**

If the 80% discharge point for our typical battery is 960 ampere-hours, then when that battery is discharged to 832 ampere-hours, or 69.3% (as in Class *B*), there is still a fraction of a workshift left in the battery. In fact, a Class *B* battery will acually last 1.15 shifts. Each of the other classes of battery will last correspondingly longer into the second shift, as shown in Table 5.

Table 5: Battery Workshift Capacity

Class	Ah Used in One Shift	Total Ah Available	Total Workshift Capacity per Truck per Charge (Shifts)
A	960	960	1.0
B	832	960	1.15
C	704	960	1.36
D	576	960	1.67
E	512	960	1.88
F	448	960	2.14

Table 5 shows how battery charges can be spread out across the two workshifts because individual batteries will reach 80% discharge at different times, depending on individual work profiles. With time, the spread will grow even more random, so that charge starts will be evenly spread throughout the two shifts. As shown in Figure 30, the net effect is to reduce the peak power demand below its absolute maximum of nearly 220 kilowatts. (The maximum peak power demand occurs when all 20 batteries are placed on

**Peak Power Demand: The use of electricity is made up of varying periods of high and low demand. Power companies build and provide sufficient generating capacity to meet periods of highest demand. To help defray the large capital outlay made to build and maintain maximum generating capacity the electric company charges customers what is referred to as a "demand charge". The charge is levied as an added cost of electricity. Two meters are used to monitor the comsumption of electricity by commercial and industrial customers: one to track kWh's and one to monitor highest average kilowatts of demand. The demand meter reads 15 minute intervals of which the two highest are used to make up an average half-hour for the monthly demand charge. Thus, it behooves a customer to limit concentration of demand for power. In the electric fork lift truck environment, this means not putting all batteries on charge at the same time or charging batteries at periods of low demand (nighttime).*

charge at once.) For example, splitting the batteries into two groups of 10 cuts the peak demand to about 198 kilowatts, a 10% reduction. And in the optimum case, in which one battery starts on charge every 24 minutes throughout the shift, peak demand falls to 130 kilowatts, a reduction of over 40%.

Figure 31 is a more general chart that shows the effect of different charging schedules on peak demand for any size fleet. To use the chart, calculate the maximum peak demand — the peak demand when 100% of the batteries are placed on charge at the same time. Then decide how many batteries you will be charging in each group and the interval between groups. (The interval is equal to 8 hours multiplied by the percent placed on charge. For example, if 5% are to be started at once, the interval is 5% of 8 hours, or 24 minutes.)

Figure 31 shows that when 5% are placed on charge every 24 minutes, the peak demand is only 59% of maximum. If your peak demand were (for example) 300 kW, the state-of-charge-based charging procedure would reduce the peak to about 177 kW. Table 6 shows the dollar impact of workshift-based vs state-of-charge-based charging.

Figure 30: Reduction of Peak Power Demand with State-of-Charge Charging Schedule

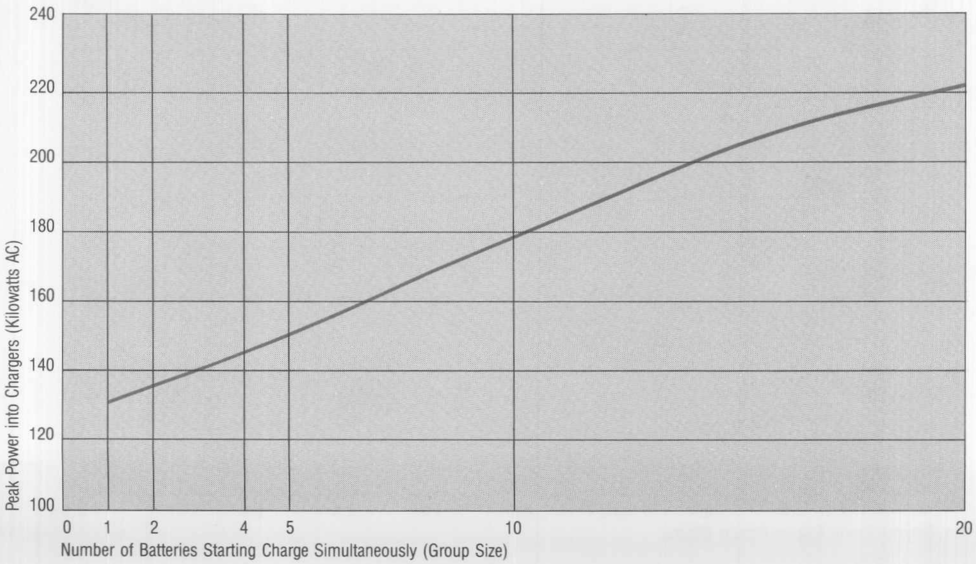


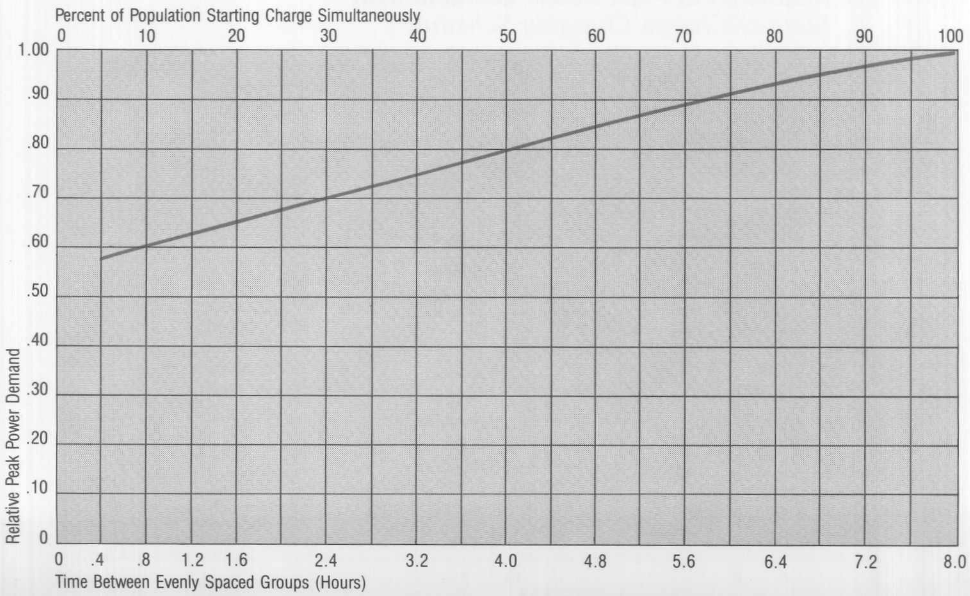
Table 6: Impact of Workshift-Based vs State-of-Charge-Based Charging on Peak Demand Charges for a 20 Truck-Fleet			
Charging Schedule		**Power Demand**	
Number of Batteries at a time	**Time between Start of Charging (Hours)**	**Peak Demand (kW)**	**Average Monthly kW Demand Charge (based on $13.78*/kW)**
20	8	221	$3050.
10	4	177	2440.
5	2	149	2055.
2	.8	135	1860.
1	.4	130	1790.

**$13.78 is the Summer kW Demand Charge levied by Consolidated Edison which serves the New York Metropolitan area (7/80).*

Capital and Labor Savings

Since each battery can last for at least one shift, and most last for part of a second, it is no longer necessary to

Figure 31: Effect of Alternative Charging Schedules on Peak Power Demand



have two batteries for every truck. The total of 40 batteries previously required for our fleet of 20 trucks is reduced to only 35, a 12% saving in capital investment. We reach this conclusion by evaluating the number of batteries required per shift as shown in Table 7.

Table 7: Batteries Required per Shift

Class	Shifts Per Battery	Batteries Per Shift	Number of Trucks	Spare Batteries Required	Next Highest Whole Number
A	1	1	1	1 = 1	1
B	1.15	0.87	2	1.74 = 2	
C	1.36	0.74	3	2.22 = 3	
D	1.67	0.60	8	4.80 = 5	
E	1.88	0.53	4	2.12 = 3	
F	2.14	0.47	2	0.94 = 1	

Spare Batteries	15
Fleet Batteries	+20
Total Batteries Required	35

From the reduction in the required number of batteries there follows, naturally, a reduction in the number of chargers required, and in the number of square feet of space devoted to charging, changing, and maintaining of batteries.

There also follows from the reduction in the number of batteries and chargers a 30% reduction in the total number of battery charges required during the year's operation of the fleet.

Under the workshift-based procedure, 200 battery charges per week supported 20 trucks, 2 shifts per day. This amounted to 10,400 battery charges per year as shown in Table 8.

In the state-of-charge-based procedure, made possible by on-board monitoring of battery capacity, there are only 35 batteries (instead of 40) to support the fleet. Thus, in 52 weeks, only 6812 charges are required for the fleet, a net reduction of 3588 charges per year.

Table 8: Number of Charges Required Annually to Support Fleet

	Old Procedure		New Procedure		
Class	Number per Class per Shift	Charges per Week	Number per Class per Shift	Charges per Class per Shift	Charges per Week
A	1	10	1	1	10
B	2	20	2	1.74	18
C	3	30	3	2.22	23
D	8	80	8	4.8	48
E	4	40	4	2.12	22
F	2	20	2	0.94	10
Totals	20	200	20	12.82	131
		×52			×52
		10,4000			6872

Every time a battery is removed from a truck and charged a certain amount of labor is involved. In addition to the business of lifting, emplacing, and breaking and making connections, there is also the labor of checking specific gravity, topping off electrolyte level, cleaning, etc., all of which must be done every time a battery is charged, regardless of its state-of-charge when it is removed from the truck.

A net reduction of 3588 charges per year (more than 1.7 per workshift for our typical double-shift, 20-truck fleet) is certainly a labor saving worth examining on its own merits.

Further, since only a small number of trucks arrive at the charging station at any given time, owing to the fact that their batteries seldom reach full discharge at the same instant, there is a considerable reduction in waiting time as compared to the workshift-based procedure previously followed. Trucks (and drivers), therefore, are more productive on the average, since less time is spent standing idle, waiting for fresh batteries.

Section 5.

WEAR AND TEAR

Overworking the Battery

Overworking the battery can have a detrimental effect on its performance and life. For example, if the truck is worked well beyond the normal rating of its battery . . . for example, by repeatedly lifting very large loads very fast for a long time . . . it is possible for the battery voltage to fall below the manufacturer's specified end point. While it is true that letting the battery recover (for a time that may extend from minutes to hours, depending on the depth of discharge) will bring it back to a useful state-of-charge, it is also true that repeated heavy discharges of this kind can damage the plates by overheating, sulfation and cell (polarity) reversal.

The makers of trucks and their electrical components offer another set of objections to overworking the battery. Operating at lower-than-specified voltage can do irreparable damage to relays, SCRs (Silicon Controlled Rectifier), contactors, motors, etc.

Causes and Effects

Damage to a battery and/or a truck caused by deep discharge is the result of failure to detect the 80% discharge point of the battery and its continued use. In the case of component failure, inadequate maintenance is often at fault.

The use of a reliable, accurate and repeatable "fuel" gage on the truck will always prevent both battery and truck damage because the "fuel" gage will always detect the 80% recommended discharge limit. A properly designed "fuel" gage with a lift lockout will actually prevent the driver from working the truck past this limit and will force him to return for battery charging.

To get the most out of traction batteries, every truck should be equipped with a reliable, accurate, repeatable "fuel" gage and controller; operating procedures should be arranged so that batteries are placed on charge only when 80% discharged; chargers should be maintained in good operating condition; and a regular routine of inspection and preventive maintenance should be followed. To do less is to waste energy, time, and money.

Epilog

Curtis Instruments, Inc. has undertaken to produce and make available this text as a part of its effort to more completely understand batteries and their use with electric fork lift trucks and other industrial electric vehicles, and to share that understanding with others related to the material handling industry.

In the future, we hope to distribute supplements to this book in the form of "application notes" addressing such areas as battery manufacturers' rating systems, how they compare and concepts of standardization of graphical displays for test data; a universal energy units conversion table; etc.

We welcome reader comments, additions, corrections (if any), etc. Keeping the information accessible and flowing will have a most definite positive impact on all our related industries.

Index

D

E

F

T

V

W